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Review

Google Earth as a Tool for Supporting Geospatial Thinking

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Abstract: In landscape planning and design, geospatial technologies (GSTs) are used to aid in visualizing and interpreting geographic environments, identifying geospatial patterns, and making decisions around information based on maps and geospatial information. GSTs are related to the different tools and technologies used to represent the earth's surface and have transformed the practice of landscape design and geospatial education. These technologies play an important role in promoting the development and application of STEM-relevant geospatial thinking. Curricula that incorporate GSTs have been used across educational levels, from elementary school through college, and have been shown to support the development of geospatial learning and understanding. The present work discusses the use of one type of GST, virtual globes, as a tool for developing geospatial thinking, with a specific focus on Google Earth. This review highlights outcomes of several studies using Google Earth in the context of disciplines related to landscape design, such as geography and earth science. Furthermore, the potential mechanisms underlying the effectiveness of this technology for supporting the development of geospatial knowledge, such as its role in facilitating data visualization and supporting student's ability to think flexibly about spatial patterns and relations, are discussed. Finally, the limitations of the current research on Google Earth as a tool for supporting geospatial learning are discussed, and suggestions for future research are provided.

Keywords: earth science; landscape planning; landscape design science; geospatial technology; geospatial thinking; virtual globes; Google Earth

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1. Introduction

Landscape planning and design deals with the description, understanding, and visualization of spaces (open spaces, surfaces, buildings, volumes, vegetation, etc.) in the landscape or in urban areas [1]. Geospatial technologies (GSTs) include different tools and technologies used to represent the earth's surface and have transformed the practice of landscape design and geospatial education. Learning in earth science can be challenging for many students because it requires being able to think temporally and spatially, and often also requires applying these types of thinking in the field [2]. Importantly, proficiency in earth science requires the coordination of these skills—often referred to as geospatial thinking—to understand the earth and how multiple interacting complex processes and systems extended in time can affect it. For example, to understand concepts such as climate and global weather patterns, students must be able to visualize processes occurring over large areas of land over long periods of time. Additionally, they need to make inferences and think critically about how these processes change as the environment changes and how these processes impact communities.

Because of the spatial and temporal challenges associated with reasoning and learning in landscape planning and landscape design science, there is often a heavy focus on using and interpreting visual representations. In fact, being able to effectively use the discipline-specific tools of representation is an important part of geospatial thinking [3,4]. In earth science and geography, these tools range from 2D representations like systems diagrams and topographic maps, such as cadastral maps, to GSTs that provide 2D and 3D representations, like virtual globes (e.g., Google Earth) and geographic information systems (GIS). Many have argued that as these tools become readily accessible and apparent in our daily lives, all students should be able to use them intelligently and may even need to use them to participate effectively in our global society. As such, recent education reform initiatives have emphasized the significance of integrating GSTs into teaching and learning [3,5,6].

Earth sciences and landscape planning and design education has begun to transform curricula by incorporating GSTs across educational levels, from elementary school through college. Many researchers suggest that GSTs promote the development and application of STEM (Science, Technology, Engineering, and Mathematics)-relevant geospatial thinking [4,7]. However, as indicated by Baker et al. [3] in their review of research on GSTs and learning, research on the impact of GSTs on geospatial thinking and student learning is fragmented and has consisted of mainly small-scale exploratory studies.

Virtual globes, such as Google Earth, are some of the most accessible and easy to use GSTs. Google Earth (GE) is remarkably useful for examining and appreciating phenomena on the face of the Earth [8]. Google Earth has been used in numerous landscape studies about geomorphology, such as channel patterns [9], coasts [10], conglomerate landscapes [11], dunes [12–15], gully erosion [16–18], desert landscapes [19], and permafrost landforms [20], among others. Other disciplines related to the land have been studied using Google Earth, such as erosion mapping [21], fluvial geomorphology [22], geospatial analysis [23], mapping the land cover [24], and landslides [25], among others.

Because spatial and temporal thinking are required for successful learning in earth science and geography, and being able to effectively use and interpret the representations and visualizations relies on geospatial skills, it is critical to understand if and how interventions with these technologies and representations in geography and earth science help to develop these skills within students. Thus, the goal of this review is to examine educational interventions in which virtual globes have been used. First, what it means to learn or understand in the earth sciences and the kinds of skills students must develop to be successful is discussed. Next, virtual globe technologies, with a specific focus on Google Earth, are described, and some strengths compared to other virtual globes are highlighted. Then, a review and examination of seventeen studies of quantitative research from the period 2012–2024 is conducted. This review summarizes and evaluates the empirical knowledge of teaching and learning with virtual globes and highlights important methodological and practical differences across the studies. The potential mechanisms underlying the effectiveness of virtual globes for supporting geospatial learning, such as their role in facilitating data visualization and flexible thinking about spatial patterns and relations, are discussed. Finally, the limitations of the present review and prior research are discussed, and suggestions for how to advance research examining the impact of Google Earth and other virtual globe technologies on students' geospatial reasoning are provided. Thus, the goal of this work is to summarize and evaluate prior research examining the impact of Google Earth on learning in the earth sciences and offer a perspective regarding how future research can more effectively develop and evaluate new interventions using Google Earth.

2. The Role of GSTs in Geospatial Thinking Skills

The earth sciences are characterized by their reliance upon and application of spatial and temporal reasoning. Specifically, successful learning in earth science and geography often requires being able to apply one's knowledge across a variety of scales. For example, geoscientists should be able to observe physical and chemical differences in ocean surface waters or in the sedimentary layers of a seafloor core and, from this information, deduce their possible impact on changes in patterns (spatial) over time (temporal). The ability to engage with this kind of task represents a great shift in thinking from where most students begin their studies, whether in primary school, secondary school, or college [26]. This kind of discipline specific spatial and temporal thinking is often referred to as geospatial thinking [3].

2.1. Geospatial Thinking

From a cognitive psychology perspective, spatial thinking represents the domain-general ability to mentally construct, manipulate, and transform spatial information including shapes, locations, paths, and relations among and between entities [4]. Geospatial thinking, on the other hand, is a domain-specific subset of spatial thinking that occurs in the context of thinking about the earth's surface and the various visual forms of information used to represent it [4]. However, various definitions for geospatial thinking have been offered. For example, some have defined geospatial thinking as the spatial and temporal thinking required for solving problems, carrying out spatial analysis, and reasoning about scale dimensions of the Earth, its landscape, and the environment [7,27–30]. Golledge [31] defines geospatial thinking as the application of spatial thinking to solve complex geographic problems, and suggests that these skills allow for visualizing, interpreting, and understanding geospatial relationships. Other definitions include a specific focus on being able to interpret and use domain-specific data and visual representations. For example, Dold and Groopman [32] defined geospatial thinking as the perception, cognition, computation, control, reaction, and understanding of physical features and geographically referenced data, and others have suggested that geospatial thinking is the reasoning required to solve problems and make decisions related to specific geographical areas, represented graphically through maps [33,34]. Similarly, the National Research Council's (NRC) committee on Support for Thinking Spatially suggested that spatial thinking in earth science recruits a combination of cognitive skills that rely on knowledge about space, the ability to use tools of representation properly, and reasoning skills [4].

Across all these definitions, there is a consensus that geospatial thinking encompasses spatial and temporal thinking in the context of reasoning about the earth's surface, the processes that impact it, and that it includes being able to make inferences from data, interpret different kinds of geographic and geologic visual representations, and integrate this information into a mental representation that can be used to generate hypotheses and predictions about how things have and will continue to change over time.

Because geospatial thinking is often considered a subset of spatial thinking more generally [3], it is important to discuss the specific types of spatial thinking skills it comprises. Spatial relations skill is a specific type of spatial thinking that is often considered the most complex and relates to one's ability to discern patterns and interrelations in stimuli and representations [35,36]. In the context of geospatial thinking, spatial relations skills are recruited when having to integrate information across representations and apply high-level reasoning processes to address specific geospatial problems. In a process called geospatial analysis, inferences, patterns, and geospatial relationships are analyzed [7].

Spatial orientation skill refers to one's ability to orientate themselves physically or mentally in space [37]. Within geospatial reasoning, its role is evident when considering tasks like using maps. To consult a map, one must orient themselves and establish their location within a space with the help of reference locations and objects. Spatial orientation skills are also recruited when consulting geographic information through geospatial technologies. In 3D representations of the earth's surface using virtual reality or augmented reality, spatial orientation skills allow one to position themselves in a certain context represented in 3D, and remain oriented during motion, that is, while navigating through that 3D virtual environment.

Spatial visualization refers to one's ability to mentally manipulate visual information through the rotation, twisting, or inverting of 2D and 3D objects [38]. In geography and earth sciences, this skill may be applied when obtaining knowledge through graphic representations like maps or diagrams [39] or when understanding dynamic 3D relationships like plate tectonics [35]. In the context of geospatial thinking skills, some have referred to this specific subtype of spatial thinking as geospatial visualization or geo-visualization, and include within it specific tasks like map reading and relief interpretation [5,7,40–42].

It is important to note that many of these skills are related to, or even dependent upon, each other. For example, spatial relations skills require spatial visualization and spatial orientation skills. It is also important to note that performance on spatial tasks has been shown to predict performance and persistence in STEM domains more generally [43], and that spatial thinking skills can be reliability improved through training [44–49]. In fact, a handful of studies have even shown that improved spatial skills via spatial training interventions can support improved STEM outcomes [50–54].

2.2. Tools for Graphically Representing of the Earth's Surface: Virtual Globes and Google Earth

According to the National Research Council [4], geospatial thinking within specific STEM domains is characterized by domain-specific spatial concepts, processes of reasoning that can be both common and discipline-specific, and importantly, the use of domain-specific tools of representation. In earth sciences, these representational tools include technologies designed to provide graphical representations of the earth's surface, ranging from traditional 2D maps to geospatial technologies capable of generating 3D maps and models. GSTs allow for visualizing, mapping, organizing, and analyzing multiple layers of geographical data. They can be used for understanding the physical environment, but also when considering decisions around environmental policy and human actions [3,4]. Using and interpreting the images and maps displayed in GSTs is not only important in the earth sciences, but also in many industrial fields. Furthermore, it has been suggested that the ability to use geospatial technologies is becoming a requirement to participate effectively as a citizen in our modern global society [55]. Thus, there has been a surge of interest in understanding how GSTs can be used in landscape planning and design education.

One of the most accessible types of GST is virtual globes (VGs). VGs are the most simplified category of GSTs and include software like Google Earth (GE) and World Wind from NASA. VGs are free web platforms for geospatial information where users can view the earth's surface, search for locations, change scales, measure distances, and use a variety of other geospatial query functions through an intuitive interface. GE is the most popular virtual globe application [56]. GE is aimed at the public as a searching and browsing tool but has also attracted many people from the earth sciences and earth science education communities because of its ease of use [57]. The interface of GE is designed to allow users to apply the features intuitively without extensive training [58]. Some have highlighted the use of VGs like GE in the early stages of geospatial education since they require fewer resources and infrastructure than other GSTs.

In addition to Google Earth, other technologies have been used to develop geospatial thinking. GIS (Geographic Information Systems) is a technology that has been shown to support geospatial thinking [59–62]. GIS involves the use of an integrated toolbox of hardware and software systems and processes designed to allow an individual to store, retrieve, visualize, and transform spatial data. Over the last three decades, GIS applications have extended beyond the field of geography and into various educational domains [62]. Despite many studies demonstrating positive learning effects for GIS-integrated learning activities, these activities may not be appropriate for all types of students across all settings. For example, software and hardware limitations can be major hurdles in using GIS in classrooms [63–65]. Furthermore, planning geospatial teaching strategies with GIS requires more preparation and instruction time, and requires qualified training for both the instructor and students [66–69]. Virtual globes like Google Earth, although they offer less functionality than other GSTs like GIS, are easier and more intuitive to use [57]. This characteristic has made them a popular tool in the early stages of geospatial education [70,71].

2.3. Using Google Earth to Support Geospatial Thinking

It is evident that spatial and temporal thinking are required for successful learning in earth science and geography, and that being able to effectively use and interpret the representations and visualizations used in these domains relies on geospatial skills. However, it is less clear how training and interventions with these technologies and representations in geography and earth science education help to foster or build these skills within students. Research has indicated that GSTs, combined with specific teaching strategies, can help students acquire geospatial thinking skills [5,49,50]. In terms of VGs like GE, many have highlighted their potential for the improvement of geospatial thinking [5,41,42,72–74].

Although it has been suggested that GE and other VG technologies can be useful tools for supporting geospatial thinking, few researchers have attempted to empirically examine this idea [3]. While many scholarly papers describe curricula that use GE at the primary, secondary, and undergraduate levels, only a small number have conducted studies assessing student learning or the development of geospatial thinking skills following the implementation of a GE intervention. Thus, the goal for the present work is to provide a systematic overview of instructional interventions using Google Earth, with a primary goal of summarizing and evaluating the empirical knowledge regarding teaching and learning with Google Earth, especially in comparison to other methods of teaching. Furthermore, while dedicated literature reviews on the state of knowledge regarding the impact of GIS on geospatial thinking and learning exist [75–77], similar literature reviews regarding the impact of GE on geospatial thinking skills and learning are lacking. Overall, this literature review aims to examine and evaluate the quality of Google Earth-based interventions designed to support the development of geospatial thinking and learning. This systematic review is structured around examining how existing empirical work aligns with the recommendations put forth by Baker et al. [3] in their proposed agenda for research on geospatial technologies and learning. Furthermore, the format and style of this review is designed to mirror that of a recent systematic review of GIS-based interventions and learning conducted by Schulze [77]. To directly address these recommendations, this literature review focuses on the following research questions:

- Q1: Do learning interventions that use a Google Earth demonstrate improved geospatial thinking and learning?
- Q2: What study designs and methods have been used to investigate the impact of Google Earth-based interventions on geospatial thinking and learning?
- Q3: What curriculum, subject matter, assessments, and outcome measures have been used to examine geospatial thinking and learning?
- Q4: How do prior knowledge or other individual-difference variables affect the impact of Google Earth-based interventions on geospatial thinking and learning?
- Q5: What pedagogical and implementation challenges should be considered when using Google Earth-based intervention?

3. Materials and Methods

The criteria carried out to select relevant studies related to instructional interventions using Google Earth have been the following:

- Documentation of the use of a virtual globe technology, with a specific focus on the use of Google Earth.
- Use of geospatial data within the learning process. That is, included studies required that students were working with georeferenced data and information describing objects, structures, events, and phenomena on the Earth's surface. Because the focus of this review is on student learning, research that focused on teachers' experiences with the technology intervention were not included.
- Demonstration of a competence or cognitive skill outcome measure. Specifically, the study needed to include competence measures such as domain-specific knowledge and skills or cognitive abilities like geospatial thinking and reasoning. Studies that examined the impact of virtual globe technology strictly on attitudes or enjoyment of the activity were not included.

Additionally, only articles that were peer-reviewed and referred to at least one concrete research question, described the methods, tools, or techniques used for data collection and analysis, described the sample by age, gender, educational level, and sample size, and discussed the research results and findings were included. Using these criteria allows for the exclusion of articles that describe conceptual or theoretical approaches without applying an intervention and measuring and analyzing specific outcomes.

3.1. Selection of Research Studies

Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol [78], the identification of relevant studies began with a keyword search across three different EBSCO databases, including Academic Search Premier, the Education Resources Information Center (ERIC) database, and the Environment Complete database. The search was conducted using the subject area keywords Google Earth, student learning, and virtual globes or digital globes for peer-reviewed academic journal articles from the period 2012–2024. Only articles since 2012 were assessed in this GE intervention search to ensure that the most up-to-date content was reviewed, given that technology is rapidly changing. This search resulted in an initial sample of 97 articles from peer-reviewed academic journals. Of the n = 97 publications initially identified, n = 17 remained for full text examination after the screening of titles and abstracts and the removal of duplicates. All the identified publications, except for two peer-reviewed conference proceedings papers, were published in international journals (Table 1). All these papers were published in peer-reviewed outlets, included at least one clear research question, had methods, materials, and results that were fully described, and included a measure of learning or cognitive skills. See Table 2 for a full listing of articles included.

Table 1. Identified articles and corresponding publications.

Journal/Proceedings *	Articles Identified
Education and Information Technologies	1
IOP Conference Series: Earth and Environmental Science *	1
International Journal of Digital Earth	1
International Research is Geographical and Environmental Education	1
Journal of Computer Assisted Learning	1
Journal of Geography	3
Journal of Geoscience Education	3
Journal of Science Education and Technology	4
Research in Science Education	1
The Geological Society of America Special Paper *	1
Total	17

Note. * Indicates a peer reviewed conference proceedings.

Table 2. Summary of the studies' main characteristics.

Reference, Year	Study Design	Sample	Intervention; Duration	Outcome Measure	Reported Effects
Bitting et al., 2017 [79]	nE, case study	Undergraduates in introductory physical geology; traditional instruction (n = 204) vs. GE instruction (n = 40)	2–4-week Google Earth project assignment completed outside of class; required finding locations, making observations and taking measurements about geologic phenomena	- 11 items from the Geoscience Concept Inventory (GCI)	- Pre–post change in GCI - No interaction with gender
Blank et al., 2016 [80]	qE, comparative design	8th grade students (n = 233) and teachers (n = 9)	6-week GE curriculum focused on constructing explanations from evidence, interpreting and analyzing data of geologic structures	- 30 items from MORSART database covering volcanoes, earthquakes, and plate tectonics - 1 reasoning ability item - 11-item science identity measure - - Math and Reading MAP scores	- Pre–post change in content - Pre–post change in reasoning - Pre–post change in science identity - GE gained more at mid-test than traditional instruction - Reading proficiency and science identity predict learning gain - No gender effect

Table 2. *Cont.*

Reference, Year	Study Design	Sample	Intervention; Duration	Outcome Measure	Reported Effects
Bodzin and Fu, 2014 [74]	nE, case study	8th grade students (n = 956) and teachers (n = 12)	4-week unit on energy and climate change using GE to explore temperature changes and climate/weather patterns	- 28 MC and 3 open-ended climate change questions	- Pre–post gain in MC concept test - Increase in open-ended items - Pre-test predicted post-test - No gender effect - Years of teaching experience predict learning
Bodzin et al., 2014 [7]	nE, case study	8th grade students (n = 1049) and teachers (n = 13)	8-week unit on energy with 14 days of geospatial learning activities (including GE) and a 1-week GIS activity	- 27 MC energy items and 11 geospatial reasoning items (data/map interpretation)	- Pre–post gain on MC and reasoning - Pre-test predicted post-test - No gender effect - Wide variability in teacher implementation of unit
Collins, 2018 [81]	qE, randomly assigned classes	8th grade students (n = 327) across; 110 in control (n = 110), GE (n = 106), and Maps (n = 111) groups	4-day unit with two large lessons on map reading and geographic features. STAT assessment given 1 month before unit and one day after completing unit	- Spatial thinking ability test (STAT) - 16 MC content items	- Pre–post gain on STAT overall - Gain in Maps and GE groups, but no change in control - Greater gain in Maps than GE - No effect of attitude towards geography or technology access - Weak correlation with travel experience
Demirci et al., 2013 [82]	nE, case study	9th grade students (n = 75)	2 h, single day lesson on coastal processes that shape coastlines	- 5-item short answer test requiring identification, description and location of coastline formations	- Pre–post gain on assessment - Students reported enjoying activity and using GE - Overall performance was low
De Paor et al., 2016 [83]	qE, randomly assigned classes	Undergraduate students (n = 396) in a general education "solar system" course with half in GE and half in PDF groups	Single lab activity that focused on a tour of a terrestrial planet either using Google Earth or PDF workbooks.	- Content test about terrestrial planets given before, immediately after, and after a short delay	- Pre–post gain for GE at immediate test, but not for PDF group - After the delay, improvement was gone and both groups performed equally
De Paor et al., 2017 [84]	nE, case study	Undergraduate students (n = 364) in a general education "intro to astronomy" class	2 h lab activity focused on seasonal change and the location of the sun's rays	- 10-item test assessing seasonal change content	- Small but significant pre–post gain in content knowledge
Giorgis, 2015 [85]	qE, comparative design	Undergraduate students (n = 75) in a structural geology course (n = 24 in GE, n = 51 in control)	3-week lab and lecture series using GE to create maps, examine strike and dip patterns, and construct cross sections	- Mental rotation test - Spatial visualization test - Penetrative thinking	- Overall pre–post gains on mental rotation and spatial visualization across classes - Pre–post gain on penetrative thinking in GE classes - Higher gains for students with more background knowledge
Gobert et al., 2012 [86]	nE, case study	Undergraduate students (Study 1: n = 225; Study 2: n = 138) in an introductory geoscience course	2 h lab session using GE to locate target countries, specify its relationship to other major landmarks, and examine changes in daylight	- 10-items on geological and geographic knowledge of Iceland - 11 items on geological and geographic knowledge of American Samoa/Tonga	- No differences in pre-test by prior knowledge or gender on either unit - Pre–post gain for both units - No difference in gain by gender or prior knowledge for both units
Hadi et al., 2021 [87]	qE, randomly assigned classes	Undergraduate students from a geography course (n = 36 in GE; n = 42 in remote sensing)	Single lab activity focused on using either GE images or remote sensing data to locate human settlements and optimal evacuation routes	- 35-item spatial thinking assessment using GE imagery - 40-item remote sensing content test	- GE class showed higher spatial performance - No differences on remote sensing content knowledge

Table 2. *Cont.*

Reference, Year	Study Design	Sample	Intervention; Duration	Outcome Measure	Reported Effects
Hsu et al., 2018 [57]	qE, randomly assigned classes	High school students split between a GE instruction class (n = 35) and a control class (n = 35)	90 min per week for 3 weeks; lessons on fluvial geomorphology, topographic maps skills, and geomorphological concepts. Observing fluvial landforms on maps or using GE	- 10 multiple choice items; half on topographic map skills and half on geomorphology concepts	- Students in GE class showed higher topographic map skills - No difference in geomorphology knowledge
Koc and Topu, 2022 [88]	nE, case study	4th grade students (n = 60)	9 h unit across 3 weeks focused on identifying countries around the world and in relation to turkey and browsing areas using street view	- 20-item "Global Connections" test - 15-item spatial visualization test - 24-item mental rotation test - Cognitive load scale	- Pre–post gain on Global Connections and MRT after unit - No effect on spatial visualization - Cog load was high in the first week but reduced over time
Kulo and Bodzin, 2013 [89]	nE, case study	8th grade students (n = 105) from five classrooms with the same teacher	8-week unit on energy with 14 days of geospatial learning activities (including GE) and a 1-week GIS activity	- 27 MC energy items - 11 geospatial reasoning items - Math proficiency levels determined by state test scores	- All students showed pre–post gain - High ability students gained more than moderate and low
Metoyer and Bednarz, 2017 [50]	qE, randomly assigned classes	10th grade honors students with different classrooms assigned to GE (n = 82) and control (n = 20)	2-day unit on central place theory; using GE or paper maps to examine spatial patterns of market centers and cities.	- Spatial visualization test (2D and 3D) - Spatial orientation test - Spatial relations test	- All groups gained on 2D/3D spatial visualization, no differences between groups - No gain on spatial orientation - Only GE group gained spatial relations measures, but gains driven by high spatial students
Monet and Greene, 2012 [90]	qE, comparative design	Undergraduate students in an introductory geoscience course (n = 68 in pre-GE classes; n = 39 in post GE classes)	Semester-long group project using GE and satellite imagery to support knowledge development around geological concepts and processes	- 11 items from the GCI	- Pre–post gains in all classes, but higher gains for GE - GE showed improvement in reasoning from geologic evidence
Xiang and Liu, 2017 [91]	qE, comparative design	9th grade students (n = 80) split across a GE class and a traditional textbook class	Five learning sessions across one full academic year focused on coastlines and coastal processes. Completed worksheets using either GE or traditional textbooks	- Essay task about changes to landscape, transportation routes, and settlement areas after a volcanic eruption - Responses coded for descriptions of spatial changes in size, shape, and contour and analyses regarding the impact of these changes	- GE group identified more spatial and temporal changes, including changes to shape and size of various geologic features - GE group was better able to make predictions regarding how human activity might be impacted by the eruption

Note. qE = quasi-experimental design; nE = non-experiment; MC = multiple choice.

3.2. Synthesis and Content Analysis Procedure

To analyze and synthesize the included research studies' findings in terms of the variables and factors that impact the effective implementation of GE-based learning interventions, narrative synthesis was used. Narrative synthesis provides a method for assembling and processing the findings and various data levels of heterogeneous individual studies, and is typically used when other forms of synthesis, like meta-analysis, are not feasible [92]. The present review used thematic and content analysis to translate data from empirical studies in terms of the main factors and variables that affect learning. The author and a trained research associate analyzed all included studies and classified them along a set of primary dimensions, including study design, sample, assessment type, reported learning outcomes, and reported implementation challenges. After individual analysis, any differences in coding were addressed through discussion.

4. Results

The results are organized according to the research questions. Each section begins with an overall summary and then goes into further detail describing differences across studies and how those differences may map onto differences in reported effectiveness of the intervention.

4.1. Do Learning Interventions That Use Google Earth Demonstrate Improved Geospatial Thinking and Learning?

The results of this review indicate that five studies compared GE interventions to traditional instructional methods and found benefits for the GE conditions. Xiang and Liu [91] compared student learning outcomes related to the geography of coastlines between 9th grade students who completed learning activities with GE and those who completed the same activities with traditional textbook lessons. Pre- and post-unit learning was assessed via an essay response item asking students to describe changes to the physical landscape, transportation routes, and human settlement areas on an island after a volcanic eruption. The results indicated that students in the GE group identified more spatial and temporal changes, including changes to the shapes and sizes of various geologic features, and were better able to make predictions regarding how human activity on the island might be impacted by the eruption than students in the traditional textbook lesson group. Hsu et al. [57] carried out a GE intervention aimed at supporting the development of topographic maps skills and geomorphology knowledge. One 10th grade classroom used GE, and another received traditional instruction with hanging topographic maps and aerial photographs. The results indicated that classes were matched at pre-test, but after the 3-week unit, the GE class demonstrated greater post-test performance. Monet and Greene [90] conducted a study in which students in an undergraduate-level introductory geology course participated in a semester-long group project using GE and satellite imagery to support knowledge development around geological concepts and processes. Learning was assessed using items from the Geoscience Concept Inventory GCI [93]. Gains in the GE intervention classes were compared to gains seen in the previous semester that did not use GE. All classes showed significant improvements from pre- to post-test, but gains were significantly higher for the GE class. In another study by Blank et al. [80], middle school students completed a 6-week Google Earth curriculum focused on constructing explanations from evidence, and interpreting and analyzing data of geologic structures, distributions of fossils and rocks, and using data to forecast catastrophic events. Half of the sample completed the unit in the Fall semester and was compared to a sample of students that received traditional instruction in the Fall but completed the Google Earth unit in the Spring. Pre-to-post change on science content knowledge, scientific reasoning, and science identity were compared between the samples in the Fall semester (one completed GE and one did not). Results demonstrated significant pre-to-post change in all measures and indicated that the GE students gained more than traditional instruction students. Finally, Hadi et al. [87] conducted a study with undergraduate students comparing a group that used Google Earth in tandem with remote sensing data as a tool to solve disaster mitigation problems to a group that only used remote sensing data. Pre- and post-study geospatial thinking skills were measured, and the students in the group that used GE showed greater gains than the control class, which used only remote sensing data.

Seven of the seventeen studies included in this review found significant pre-to-post-test gains for students in a GE intervention, but these gains were not compared to a control group. In two studies conducted by Bodzin and colleagues [7,89], 8th grade classrooms completed an 8-week unit on energy that incorporated 14 days of geospatial learning activities. Before and after the unit, students completed a geospatial thinking and reasoning assessment, including items requiring geospatial analysis for making inferences about geospatial relationships and items that assessed energy resource content knowledge. In both studies, students improved their geospatial reasoning and content knowledge after completing the unit. Similar results were obtained in another study by Bodzin and Fu [74] that implemented a GE unit on climate change such that students' climate change knowledge improved after the unit. Bitting et al. [79] examined an out-of-class GE assignment that spanned a 2–4-week interval in two undergraduate-level introductory physical geology courses, one taught online and one taught face-to-face. The project covered plate tectonics, earth materials, volcanoes, sediments, fossils, and geologic time. All students completed a pre- and post-test composed of 11 items from the GCI [93]. There were no differences in pre- and post-test performance between the face-to-face and online class formats, but all classes showed pre-to-post improvement. Gobert et al. [86] examined the impact of prior geoscience coursework and gender on learning with GE in an undergraduate sample across two studies. Study 1 examined the impact of a GE curriculum on understanding of the geography and geology of Iceland, and Study 2 focused on the Tonga region in the west Pacific. Across both studies, there were no differences in pre-test scores as a function of gender or prior geoscience coursework, and post-test scores were significantly higher than pre-test scores. Koc and Topu [88] used Google Earth as a tool for supporting 4th grade students' world geography knowledge and spatial thinking skills. After the 6-week unit, results showed significant pre- to post-test improvement in students' geography knowledge and a measure of mental rotation skill. Finally, in a study by Demirci et al. [82], 9th grade students completed a single lesson on coastal processes that shape coastlines using GE. Results indicated significant pre-to-post gain in a measure assessing student ability to name, describe, and locate different types of coastline formations.

The last five studies included in this review examined the effect of a GE intervention on pre-to-post gain, but the outcomes were mixed or less successful for improving geospatial thinking. For example, Metoyer and Bednarz [50] conducted a two-day unit on central place theory, focusing on understanding the availability of market services in human or residential systems. High school students used GE or paper maps to explore the assumptions of central place theory and the spatial patterns of market centers and cities. Performance in these groups was compared to a traditional instruction control class. All three groups showed improvement on 2D and 3D spatial visualization after the unit; however, the gains did not differ between conditions. Giorgis [85] compared spatial skill development in undergraduate structural geology courses that used GE lab modules on inclined contacts, strike and dip, and mapping folded rock to those that did not. All classes showed gains on the domain-general spatial measures, and there was no difference between the GE and non-GE classes. Collins [81] compared gains in 8th grade students' spatial thinking skills after completing a geography curriculum using GE, paper maps, or traditional instruction. Spatial scores, as measured by the Spatial Thinking Ability Test [94], improved pre-to-post in the paper map and GE groups, but not in the control group. However, improvement was greater in the paper map condition than in the GE condition. De Paor and colleagues [83,84] have also obtained mixed results regarding GE learning interventions. In one study, De Paor et al. [83] had students complete virtual tours of other terrestrial planets (e.g., Mercury, Venus, Mars, the Moon) via a Google Earth-based intervention or complete the same activities with content-matched textbook-like PDF handouts. Both classes showed pre–post improvement, and the GE group showed greater immediate gains than the PDF condition, but this advantage was gone at a delayed post-test. De Paor et al. [84] also used GE in a unit on seasonal change for undergraduate-level introductory astronomy students. While post-test performance improved overall, there was wide variation in performance, with about 25% of students showing no change, and 18% performing worse.

Taken together, the reviewed set of studies indicates that the impact of Google Earth-based curricula and intervention on geospatial thinking and learning is unclear. While several studies indicate that Google Earth can be an effective tool for supporting geospatial thinking and learning, many of the studies lack comparison conditions, there is wide variation in the enactment of interventions, and there is wide variation in how learning or geospatial thinking was assessed. These differences and how they impact the interpretability of this body of research will be discussed next.

4.2. What Study Designs and Methods Have Been Used to Investigate the Impact of Google Earth-Based Interventions on Geospatial Thinking and Learning?

As shown in Table 2 and highlighted in the previous section, the results of this review indicate that none of the included studies can be classified as true experiments because, by definition, true experiments require random assignment to conditions at the individual participant level. None of the studies included in this review randomly assigned individual students to conditions. However, according to this classification, nine out of the total sample of seventeen studies can be classified as quasi-experimental studies because whole classrooms were randomly assigned to treatment conditions, with at least one classroom serving as a control or comparison. Of these nine studies, three compared classes that used a Google Earth-based curriculum to control classes that completed the same assessments but did not complete learning activities that were matched to the Google-Earth classes [80,85,90]. That is, in these studies, pre–post gains were compared between classes that completed active, hands-on Google Earth learning activities to control classes where learning activities were not specified. The remaining six quasi-experimental studies compared pre–post learning between a group that completed a Google Earth-based learning activity and a group that completed a matched activity using static representations such as paper maps, wall maps, or aerial photos and data. The remaining eight studies used non-experimental designs. These non-experimental studies conducted research in the form of case studies, meaning that there were no control groups or comparative analyses. Rather, these studies all examined pre- to post-test change in performance for a single sample, without comparison to another group. Furthermore, most of the quasi-experimental studies were limited in the broader claims they can make regarding their results because many did not account for or control for any interfering factors across groups. Specifically, most of these studies did not demonstrate that the GE and comparison groups were matched prior to examining differences in post-test scores. Of the nine quasi-experimental studies, only three [57,80,85] specifically mention comparing or controlling for baseline skills or prior knowledge to ensure the groups were matched.

Not only were there differences in the experimental designs of the studies included in this review, but there were also large differences in the number of participants across the studies, and high variability in the form and duration of the individual interventions used. In terms of sample size, the smallest study [88] included only 60 primary school students, while in comparison, the largest study included over 1000 students from 13 different 8th grade science classrooms [7]. A similar situation was found regarding differences in the duration of the interventions, with some ranging from single one- to two-hour lab sessions [82–84,86,87], to multi-week lessons and learning units [7,57,74,79,80,85,88,89,91], to comparisons of courses over multiple semesters [90].

4.3. What Curriculum, Subject Matter, Assessments and Outcome Measures Have Been Used to Examine Geospatial Thinking and Learning?

As indicated in the criteria used for selecting included studies, all studies in this review aimed to support geospatial thinking and learning with Google Earth in some kind of hands-on learning situation. However, analysis of the interventions and curricula that were implemented across studies indicates that there were wide variations in the content and subject matter, as well as variations in the assessment and outcome measures used. At the level of higher education, Google Earth-based activities were primarily used in hands-on laboratory exercises or for larger semester-long projects. Typically, the content area of these courses or projects was introductory physical geology [79,85,86,90], but there were a few exceptions. One GE intervention was developed for a planetary course [83], one intervention was designed to address the understanding of seasonal change [84], and one was designed to address the understanding of human geography and disaster mitigation [87]. When looking at GE-based interventions or curricula for school-aged populations, the focus was more varied. Several studies were focused on geography-based concepts [50,81,88], several on climate and energy [7,74,89], and two on coastlines and coastal processes [82,91]. Only two studies focused on content related to geology or geologic structure [57,80].

With GE curricula and interventions designed to support learning of different geospatial content, it is also the case that the studies differed in the types of assessment used to measure geospatial skills and learning. Most of the studies (13 of 17) assessed content-specific geospatial thinking and learning, and four studies focused on changes in performance on psychometric measures of spatial thinking, including mental rotation, spatial visualization, and spatial orientation. Of the studies that assessed content specific knowledge, there was variation in the types of questions and items used. For example, several studies used short-answer or essay-based questions that required students to demonstrate comprehension or reasoning ability, some used assessments that required students to demonstrate their map reading skills, and some studies used standardized assessment instruments taken from prior geoscience education research or from school-based standardized assessments.

4.4. How Do Prior Knowledge or Other Individual-Difference Variables Affect the Impact of Google Earth-Based Interventions on Geospatial Thinking and Learning?

An important factor to consider in any educationally relevant research is who the different kinds of learning interventions are most effective for. Thus, considering individual-difference factors such as gender, prior knowledge, interest, and other cognitive skills or abilities is important. For example, educators and researchers may want to know if some baseline level of geoscience, geography, or technology knowledge is required for Google Earth-based curricula to be effective. Many of the studies included in this analysis reported on additional measures and factors beyond the geospatial thinking and learning measures. Five studies examined differences in pre–post gain as a function of gender [7,74,79,85,86], but only one indicated a difference between males and females [74]. Several studies examined the effect of prior knowledge on post test scores. Bodzin et al. [7] and Bodzin and Fu [74] found that pre-test score was a significant predictor of post-test score, and Giorgis [85] found that only students with high prior knowledge showed significant pre-to-post improvements on a domain-specific measure of spatial (penetrative thinking). However, Gobert et al. [86] found no differences in learning as a function of prior knowledge across two different studies. Several studies examined differences across students as a function of their scores on standardized math and reading assessments. Blank et al. [80] found that students with higher reading ability gained more from pre to post, and Kulo and Bodzin [89] found that while all students gained from pre to post, students with high math proficiency gained more than students with moderate or low math proficiency. Surprisingly, considering the role of spatial thinking skills in geospatial thinking and learning, very few studies examined differences in learning gain as a function of spatial skill. Hadi et al. [87] reported a correlation between score on achievement and score on spatial skill, suggesting that perhaps spatial skills are required to effectively learn from a Google Earth-based intervention. Similarly, Metoyer and Bednarz [50] found that gains on the content-dependent and -independent spatial relations test were driven primarily by the highly spatial students in all conditions, regardless of the use of GE. Finally, two studies examined the relationship between pre-to-post gain and science attitude. Blank et al. [50] found that students with higher self-reported science identity gained more, while Collins [81] found no correlation between gain and attitudes towards geography.

4.5. What Pedagogical and Implementation Challenges Should Be Considered When Using Google Earth-Based Intervention?

A critical factor to consider when examining the impact of any technology-based intervention or curriculum on student learning is how access to and use of the technology impacts learning. For example, differences in how a technology is presented or interacted with, how consistent access is, and how much skill is required to use it can all greatly impact its effectiveness [69]. In the present review, studies varied widely in how students were presented with and interacted with the Google Earth technology. For example, in some studies, students only had access to a single screen or computer, and thus, the unit activities had to be conducted in small groups [57,88], while in other studies, students had access to individual computers in their classrooms or in a school/university computer lab [7,50,74,80–87,89,91], and in others, all GE activities were completed at home as homework or course projects [79,90]. Another issue regarding technology access that was mentioned in several studies was access to adequate internet, as the program sometimes froze and disrupted implementation [81,82,88].

Finally, several researchers mentioned challenges with curriculum implementation because students and/or teachers lacked knowledge regarding how to use many of the tools in Google Earth. For example, Bodzin and Fu [74] suggested that while Google Earth does allow for richer and more meaningful scientific inquiry than many standard science units, curriculum implementation may be impacted by the experience level of the teacher. Similarly, several researchers suggested that students may require more instruction around the tools in GE for the intervention to be maximally effective [57,83,85,86,89,90].

5. Discussion

This section is organized around three focal points of discussion. First, an overview of the knowledge added from this review and a discussion of the possible mechanisms underlying the effectiveness of Google Earth and other virtual globes for supporting geospatial thinking and learning will be provided. Next, limitations regarding the scope and quality of this review will be discussed. And finally, implications and suggestions for future research will be provided.

5.1. Potential Mechanisms That Support Geospatial Thinking and Learning

Taken together, most of the studies examined demonstrate that GE can be a powerful tool for supporting conceptual knowledge in geography and earth science, and geospatial thinking skills such as topographic map reading, penetrative visualization, and understanding the relationship between geographic and geologic features and human systems. Across these studies, several suggestions have been made regarding what mechanisms may underlie the effectiveness of GE interventions for supporting geospatial skill development. One primary argument is that GE facilitates geospatial reasoning because it better supports 3D visualization than traditional 2D tools [7,57,85]. In particular, the 3D visualization provided by GE allows students to develop a better sense of place, especially when learning about unfamiliar locations [88,90]; better supports visualization of change with the historical imagery function [95]; allows for the combination of top-down and ground-level perspectives; and allows students to change scales in a way that traditional maps do not [91].

Beyond the visualization benefits provided by GE, virtual globe technologies may also support geospatial thinking via increased motivation and engagement. Bitting et al. [87] suggest that the realistic imagery of real-world locations may engage students cognitively and affectively. Furthermore, GE allows for more active engagement and personalized interaction by giving students control over functions like zooming, accessing historical images, and tilting [91,96]. Patterson [41] argues that tools like GE can be empowering for students because they support them in completing complex tasks and give them more latitude in designing their own projects and investigating their own questions. Similarly, Hadi et al. [87] found that using Google Earth to support geospatial thinking and learning encouraged greater student interaction with media and student-to-student interactions.

Instructional scaffolding is also critical when using GE in the classroom. Even though GE is easier to use than other GSTs, interventions and units that incorporate GE are not without extensive planning and preparation. For example, some studies have included overview and introductory lessons on GE prior to starting the target learning activities [7,50,74,80,81,88–91]. The activities in many of these studies were highly scaffolded and progressive, such that students started with general map reading activities in GE before completing activities requiring inference generation and analysis [7,57,74,86,89,90]. Moorman and Crichton [97] suggest that technologies like GE require learners to make many decisions about scale, viewing area, and attribute data, and that making these processes more explicit through scaffolded instruction may better support the development of geospatial literacy.

While this review has generated an overarching set of topics that should be considered when conducting research on Google Earth and virtual globe-based interventions and provided suggestions regarding some of the mechanisms that make GE effective for learning, it must be emphasized that the driving questions regarding how and why GE supports geospatial thinking and learning cannot be answered conclusively here. As indicated by the synthesis provided earlier, there is much heterogeneity between the examined studies, which impacts the kinds of inferences and claims that can conclusively be generated. For example, the present examination found that the sample of studies used different methods of assessment and analysis. This lack of standardized measurement, methodology, and evaluation generates a consequent uncertainty for the interpretation of results. For example, many studies do not include a control or comparison group. Without a comparison group, it is difficult to determine if learning gains are due to the use of GE, the result of testing effects (i.e., gains from taking a test twice), or due to another unknown factor. In fact, several authors even suggest that their results could be due to testing effects [50,84,85]. Furthermore, in cases where a comparison group was included, often the learning activities were not well matched or were not described in sufficient detail to determine their match. For example, in one study, the comparison group used paper maps requiring the representations to be mentally "overlayed" on top of each other, whereas these same representations were given simultaneously in the GE group [91]. The act of having to mentally integrate multiple representations increases cognitive load [98] and may require greater spatial thinking skills [99]. Similarly, in another study, students in the GE class worked with different instructional examples than students in the comparison class, and information regarding the alignment of these examples was not provided [57].

The present review of GE intervention research also reveals that there is no standardized method to assess learning from GE interventions. Some assessments could have been described in greater detail and/or provided data on the validity and reliability of the measures. For example, one study used an essay assessment and coded for the presence of words thought to reflect different spatial reasoning processes but did not provide reliability data for the coding or a rationale for the coding procedure [91]. In other cases, assessments included multiple-choice questions without reliability or validity data, and did not describe whether memory of basic content or more complex understanding and inference generation was being evaluated (e.g., [7,50,86]). There were also cases in which it was difficult to determine whether the assessments were of the appropriate level of complexity (e.g., [79,81,88]). In addition, only one study assessed learning after a delay to capture long-term retention [83].

Data analysis methods used in the reviewed studies could also be improved to strengthen interpretability. Many studies used t-tests to examine differences in pre-to-post gain between groups but did not report whether groups were matched on pre-test. When performing multiple analyses, it is best practice to use fewer tests incorporating more dependent and independent variables simultaneously (e.g., ANOVA, multiple regression). When multiple t-tests are used, there is greater probability for type 1 error (finding a false positive result). Including effect sizes for all tests would also help to strengthen the interpretability of results. Additionally, when examining individual differences like prior knowledge or spatial abilities, it is good practice to treat these variables as continuous and perform regression analyses rather than reduce variance and create ability level groups (e.g., [50,80,85,89]).

5.2. Limitations of the Present Review

Since the value of a systematic review is directly dependent upon the validity of the methods used to minimize bias, the limitations of the present work need to be critically discussed. First, the selection and synthesis of the studies included in this review were completed according to the judgment of the author of this review and a research associate.

Despite following a strict procedure for identifying relevant research and having authors with many years of experience in both geography, landscape planning and design, and educational intervention research conduct, in the synthesis procedure, it is always possible that important literature was missing or that evaluations of the included studies are flawed. However, seeing as this is the only known review of virtual globes and a Google Earth-based curriculum on students' geospatial thinking and learning, it may serve as a critical springboard for future reviews and research on the topic. It should be noted that this review only includes peer-reviewed articles that were published between 2012 and 2024, but was also limited to English-only publications that the author had full access to. Therefore, this critical review runs the risk of publication bias by excluding unpublished works like dissertations, non-peer reviewed work such as conference presentations, or works that the systematic search failed to include for some other reason. However, systematic literature review, like meta-analysis, should always contribute something new to the field, and there is no single correct and agreed-upon way to perform one [100]. Especially in the case of empirical education research, personal, social, contextual, and technical factors must be considered, and thus, the validity of this review is limited to the scope of the results of the respective individual studies.

5.3. Future Research Directions

The results of this systematic review provide a range of directions for future research on the impact of virtual globes and Google Earth-based interventions on geospatial thinking and learning.

First, the studies selected in our GE intervention research could be complemented by considering the impact of individual student characteristics, including prior knowledge, geospatial thinking, or working memory capacity. Furthermore, some suggest that prior knowledge in geography, geoscience, or technology may be relevant because it can allow students to solve problems in different ways and rely less on spatial skills; however, few systematically examine this. Cognitive capacities such as working memory and geospatial thinking are also relevant to consider. Working memory is involved in the control, regulation, maintenance, and manipulation of information, and is relevant in nearly all learning scenarios [101]. In working with complex visualizations like GE, working memory may be required for keeping track of quickly changing information, or for aligning information across multiple representations. In the works highlighted in our GE intervention research, working memory is relevant to consider when students must compare maps, recall information from previous examples, know how and when to change map features, and more. Spatial thinking skills and, concretely, geospatial thinking skills are also important to consider. Despite the well-known role of spatial skills in STEM reasoning, few GE invention studies include measures of spatial thinking.

Other factors related to the implementation of the interventions and units should also be considered. Understanding the type of scaffolding required for different concepts and topics, and for different age groups of learners, is essential for creating interventions that are maximally effective. Research should more systematically examine the types of training students and teachers need to be able to use Google Earth and other similar technologies. Furthermore, research should systematically explore the types of interactions learners have with Google Earth to determine which ones are driving the greatest gains. With so many unique and powerful tools for visualizing the world, it is important to identify which tools support different kinds of geospatial thinking and learning. It is also critical that future research examine and compare the impact of GE-based learning interventions to the impacts of other popular GSTs such as GIS. These tools are not interchangeable and may offer different support and opportunities for geospatial thinking and learning. These kinds of comparative experiments should be considered in future research.

Furthermore, research examining the impact of various GSTs on learning should be more systematic and deliberate about what research questions to address and how to address them. In the present examination, it was clear that different researchers approach the problem from different perspectives. Even starting with basic definitions, there was a mare magnum of terms used (e.g., geospatial intelligence, geographic thinking, geospatial reasoning, geospatial thinking, spatial thinking, spatial relations, penetrative visualization) when discussing the specific types of thinking and reasoning required in the earth sciences and geography. These basic definitions and concepts need to be unified. Similarly, the community needs to work towards developing a clear understanding of the various components of geospatial thinking and their interrelationships. While researchers in cognitive psychology have been working on defining some of these cognitive factors for decades, it is only with the help and input of domain experts that these components can be determined in the context of domain-specific geospatial thinking. Ultimately, research on GE interventions in education still has challenges to overcome. Going forward, experts in geography, earth sciences, computer science, psychology, and education must work collaboratively to conduct science education research that is theoretically driven, evidence-based, methodologically sound, and generalizable. And even after that work is done, researchers, teachers, and industry experts must work to implement the findings of that work and put best those practices into action.

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