

The design, implementation, and evaluation of a digital interactive globe system integrated into an Earth Science course

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Abstract The aim of this study is to design and implement a digital interactive globe system (DIGS), by integrating low-cost equipment to make DIGS cost-effective. DIGS includes a data processing unit, a wireless control unit, an image-capturing unit, a laser emission unit, and a three-dimensional hemispheric body-imaging screen. A quasi-experimental study was conducted to evaluate the learning effectiveness of our system. A total of 105 junior high-school students from Taiwan participated in this 8-week experiment. The students were divided into three individual groups of 35 students each, with one control group and two experimental groups (EG1 and EG2). The results of one-way mixed design ANOVA indicated that participants in the experimental group, who used the DIGS, outperformed the other two groups, in the post-test as well as in the delayed test. These findings demonstrate that the proposed DIGS can effectively enhance the performance of the learners in an Earth Science course.

Keywords Digital Earth · Earth Science · Interactive learning environment · Learning outcomes

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Introduction

Various models of the Earth, such as globes showing countries, continents and other aspects of the Earth, are often used as teaching aids for formal or informal educational teaching in schools, museums as well as other education institutions. In recent years, as technologies progress, many researchers have attempted to project images utilizing Earth simulation software onto screens or as spherical representations, in the form of digital teaching aids (Ancona et al. 2002; Wu et al. 2010; Xie and Reider 2014; Zhu et al. 2008). For example, Philip M. Sadler invented the *Starlab* portable planetarium in 1977 (see <https://www.cfa.harvard.edu/news/2014-24>). *Starlab* has been used for teaching astronomy (see also <http://starlab.com/>), but it is expensive. Berry et al. (2007) developed a spherical display system known as *Aggie Orb*. In this system, visual effects were produced by multicolor LEDs rotating along a spherical trajectory. The heavy weight of *Aggie Orb*, which is approximately 200 lb, and its large size, are major limitations of this system. Therefore, the high costs and complexity of the equipment required, current display systems simulating the Earth are not generally available for classrooms. This article describes the development and use of a three-dimensional (3-D) simulated Earth system, utilizing existing classroom equipment to improve learning performance in the Earth Science course. Our system projects a 3-D spherical image of the Earth. In addition, this system allows the operator to use a simple handheld wireless control device to interact with the 3-D interactive globe system.

Theoretical foundations

Considerations from the cognitive theory of multimedia learning (CTML) and cognitive flexibility theory (CFT) were integrated to design digital interactive globe system (DIGS).

Mayer (2001) proposed CTML, which is based in part on dual coding theory (Paivio 1986) and cognitive load theory (Chandler and Sweller 1991). DIGS incorporated five principles of CTML to improve learning: (1) modality principle, states that learners learn better from graphics and narrations than from animation and on-screen text, (2) temporal contiguity principle, states that learners learn better when corresponding words and pictures are presented simultaneously rather than successively, (3) spatial contiguity principle, states that learners learn better when corresponding words and pictures are presented near rather than far from each other on the page or screen, (4) redundancy principle, states that learners learn better from graphics and narration than from graphics, narration and on-screen text, and (5) multimedia principle, states that learners learn better from words and pictures than from words alone. According to CTML, when symbolic information or text is presented, information is processed through the visual channel of the working memory. However, when narration text is presented, information is processed through the auditory channel. On the other hand, when multimedia information, for example, animation with spoken narration is presented, it can be processed through two channels (visual and auditory) in parallel. This type of information processing is more efficient and reduces the load placed on working memory, according to dual coding theory and cognitive load theory.

Spiro and Jehng (1990) proposed CFT, which builds upon constructivism. Constructivism refers to a naturalistic epistemology that recognizes the significance of an active learning process in which learners construct new knowledge from their current or prior

knowledge (Jonassen 1994; Spector 2015). Spiro and Jehng (1990) defined cognitive flexibility as “the ability to spontaneously restructure one’s knowledge, in many ways, in adaptive response to radically changing situational demands” (p. 165). CFT helps the learners to develop a deeper understanding of complex concepts and to apply that knowledge in real-world contexts (Spiro et al. 2003). This is consistent with the findings reported by Dörner (1996) in *The Logic of Failure*, which promotes rich multimedia and interactive simulations to support learning in complex domains.

CFT recommends that learning activities must provide multiple representations of the contents to discover and explore the complex problems (Spiro et al. 1988). Chieu (2007) proposed operational criteria of CFT and identified four important components of learning systems: (1) learning contents (e.g., text, images, audio, video, simulations), (2) pedagogical devices (e.g., tools provided for learners for exploring learning contents), (3) human interactions (e.g., means for engaging tutors and learners in exchanges), and (4) assessment (e.g., post-tests for determining whether learners have achieved learning objectives). Interactive features in DIGS are well aligned with CFT. In addition, changes in conceptualizations can be determined by simple tests, and it is a change in how a student thinks that is compatible with cognitive flexibility. Also, CFT is consistent with multiple forms of representations, including visualization and DIGS and its impact on learners involves multiple forms of representation.

Many empirical studies have shown the positive effects of CFT in information and communication technology-based learning environments (Dörner 1996; Fitzgerald et al. 1997; Goeze et al. 2014; Jacobson and Spiro 1995; Lima et al. 2004; Lowrey and Kim 2009; Mendes et al. 2001; Zottmann et al. 2012; Zydney 2010; Zydney and Grincewicz 2011). For example, Zydney and Grincewicz (2011) developed a software program based on CFT for socio-scientific problem solving. The results showed that the software helped the students to learn scientific processes, which promotes critical thinking and deeper learning (e.g., seeking and explaining evidence). In another study, Mendes et al. (2001) applied CFT to teach hypermedia-engineering principles. They found that the students who were exposed to CFT-based teaching performed better than those exposed only to traditional methods.

Incorporated with the above-mentioned principles of CTML and CFT, DIGS can provide learning contents (graphics, animations, simulations, etc.) with narrative descriptions simultaneously to make learning more effective and interactive.

Existing Digital Earth (DE) systems

Zhu et al. (2008) defined DE as “a virtual presentation of the planet based on geographic coordinate, and is an information system with tremendous amount of multiple resolutions and multiple scales data as shown in multiple dimensions. It can visualize the real Earth and represent historical phenomena in a digital way by using the large amount of data of the Earth, and utilizing the computer techniques, image and graphic technique, network technique, virtual reality and so on” (p. 118). Existing DE systems such as Google Earth (GE), science on a sphere (SOS) Earth system and Geo-Cosmos are new developments in visualising 2-D and 3-D representations of Earth. Demirci (2009) found that teachers are very positive towards geographic information systems (GISs) in spite of some hardware and software barriers. This positive attitude will be helpful for the development of good teaching plans in geography.

Geospatial technologies are growing in use and popularity as a result of improvements in computational power and easier access to geospatial data (Milla et al. 2005). Patterson (2007) advocated the use of GE (<https://earth.google.com/>) because it is a potential tool to enhance teaching methods in geography. Doering and Veletsianos (2008) found that students were motivated to use geospatial technology like GE for their class assignments. They also found there was a lack of geospatial technology-based curricula in the formal education systems.

GE maps the Earth by the superimposition of images obtained from satellite imagery, aerial photography and GIS onto a computer screen, but GE has some limitations, some of which are technical and some of which as a result of a 2-D representation. GE cannot work without an Internet connection (Patterson 2007), and it also needs high bandwidth for good performance. Wang et al. (2013) mentioned that GE required some information technology skills and therefore, it may not be suitable for the students who are not proficient in handling technology. Zhu et al. (2014), also highlighted two important limitations of the current DE systems: (1) inability to represent the whole Earth as a 3-D model clearly and (2) DE systems lack the necessary advanced functions in 3-D visualization.

The cost of current commercial DE systems is a matter of concern (Vanhoenacker 2013). Table 1 shows a comparison of the DIGS with selected commercial existing DE systems. Compared to the existing DE systems, DIGS offers instructors some additional features like real time marking and drawing functions, extensive control, including display management by walking around (MBWA), and more. Instructor led MBWA positively affects instructional practices, which results in better student learning achievement (Keruskun 2005). DIGS is an important didactic development in affordable Earth system global displays for education.

According to Roblyer (2005):

When there is a clear need for a better instructional method than those used in the past, researchers can propose that a given technology-based method is the best choice because it offers the combination of relevant symbol systems, processing capabilities, and logistical feasibility to address the need—and then do research to support that it has this relative advantage and clarify the conditions under which it works best (np).

DIGS is aligned with Roblyer's (2005) argument. Lower cost and being able to function in low bandwidth areas are the other most important features of DIGS that makes this system relatively advanced than the other existing DE systems.

Table 1 Comparison of commercial Digital Earth (DE) systems with DIGS

Features	DIGS	SOS	Geo-Cosmos
Cost (USD)	200	43,000	100,000
Dynamic information	Yes	Yes	Yes
Static information	Yes	Yes	Yes
3-D effect	Yes	Yes	Yes
Real time mark and draw function	Yes	No	No
Extensive control and MBWA	Yes	No	No
Application in the classroom	Yes	No	No
Create your own content	Yes	No	No

Need for this study

When reviewing current DE systems, three considerations need to be clarified: (1) none of these aforementioned DE systems offer didactic development in Earth Science courses for formal education, (2) the above-mentioned DE systems do not offer any opportunity for the instructors to incorporate appropriate teaching–learning materials into the systems, (3) most DE systems are too costly to be included into the mainstream education systems in developing countries, and (4) although GE is free, it lacks interactive functions and features found in the DE systems in Table 1. Based on the above considerations, the aim of this study is to design and implement a DIGS to be integrated into a general junior high-school Earth Science course.

DIGS architecture¹

Hardware

DIGS involves a data processing unit, a wireless control unit, an image capturing unit, a laser pointing device, and a 3-D hemispheric body imaging (HBI) unit—a kind of 3-D screen (see Fig. 1). The 3-D HBI screen is designed to display the output image from the data processing unit. The laser emission unit is for emitting a laser spot on the output image.

Software

DIGS utilizes the Unity game engine. Unity is a powerful game developer engine. For independent developers, this software breaks the time, platform and cost barriers (<https://unity3d.com/>). We selected this cross-platform software as it supports many types of art and design resources.

Operating process with an example

In the first step, we imported real-world height maps from the website of <http://terrain.party/> into Unity software to develop different Earth Science course materials (see Fig. 2). This website is available free to download the maps based on our needs. Using Unity software, real-world heights maps were converted into 3-D terrain models (see Fig. 3).

DIGS is a user-friendly system in the classroom. DIGS allows the users to navigate from one concept to another many times according to their pace. This provides an opportunity for interaction between the user and the system. Users can use the functions like *click*, *zoom in–out*, *rotate*, etc., based on their learning needs. For example, a lesson plan on Argentina terrain needs to follow the following steps:

Step 1 users need to select a country on the system to teach in the classroom.

Step 2 the system will display the selected country to the users on the interface.

Step 3 users need to double-*click* the selected country, and the system will display the 3-D terrain model of the country and need to use the *zoom in* function to view the selected country for more details (see Fig. 4).

¹ To know more information about technical description of DIGS please contact the authors.

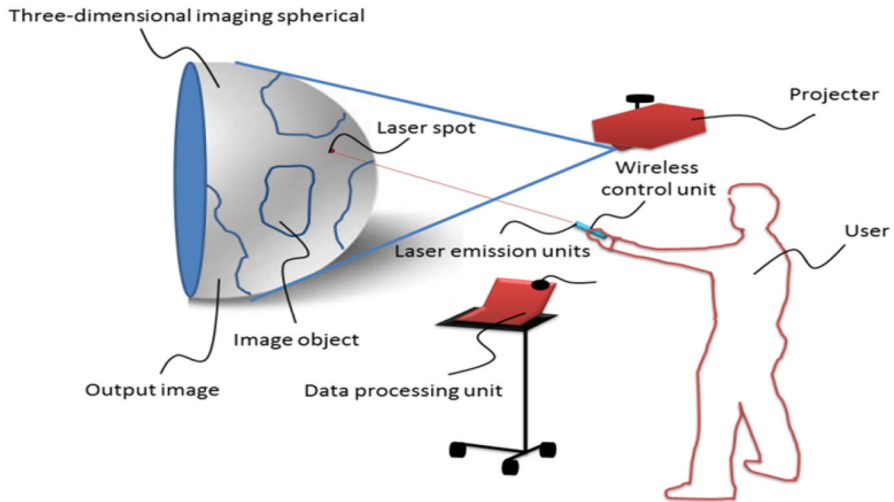


Fig. 1 DIGS architecture

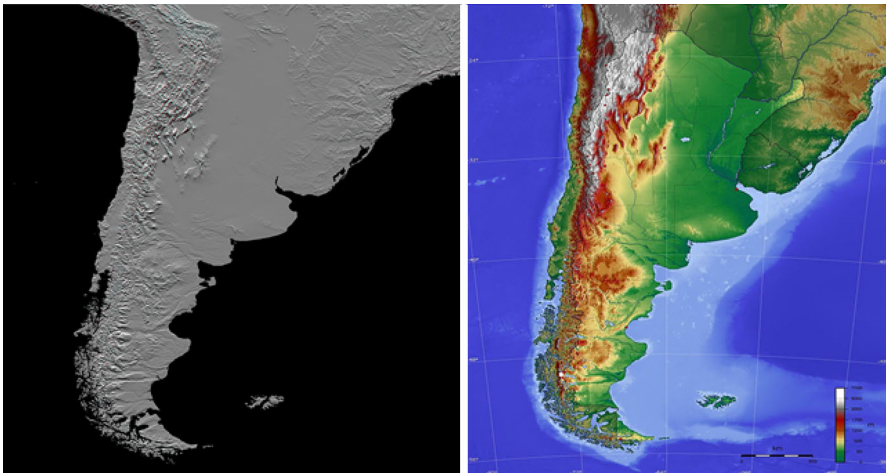


Fig. 2 Height-map downloaded from <http://terrain.party/>

Step 4 users can use the *rotate* function to view the 3-D terrain model from any angle (see Fig. 5).

Step 5 users can use the *zoom in* function to focus on any particular are of the 3-D terrain (see Fig. 6).

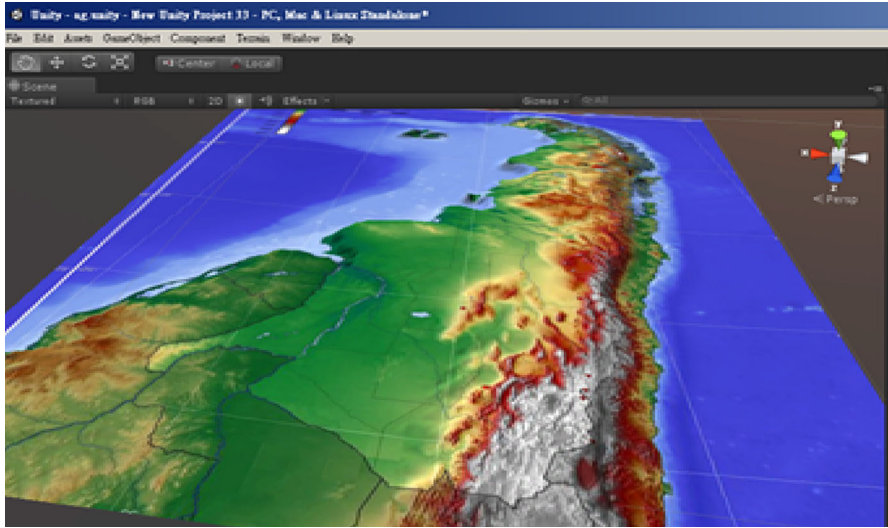


Fig. 3 Example of 3-D terrain model developed by Unity



Fig. 4 Click and zoom in functions in DIGS

Scientific contents incorporated in DIGS

This interactive system allows the users to access various Earth observation data collected from different international sources, e.g., National Aeronautics and Space Administration (NASA), US Geological Survey, National Oceanic and Atmospheric Administration. The content includes *Solar system*, *Earth tectonic system*, *Global carbon-dioxide map*, *Global ocean temperature*, *Global thundering*, *Global hurricane*, and *Global forest map*. For more details (see <https://www.youtube.com/watch?v=QOUPhyOB9o&t=140s>).

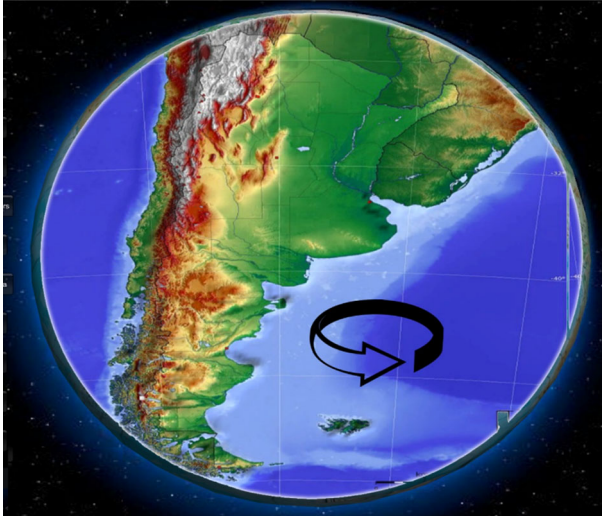


Fig. 5 The rotate function in DIGS

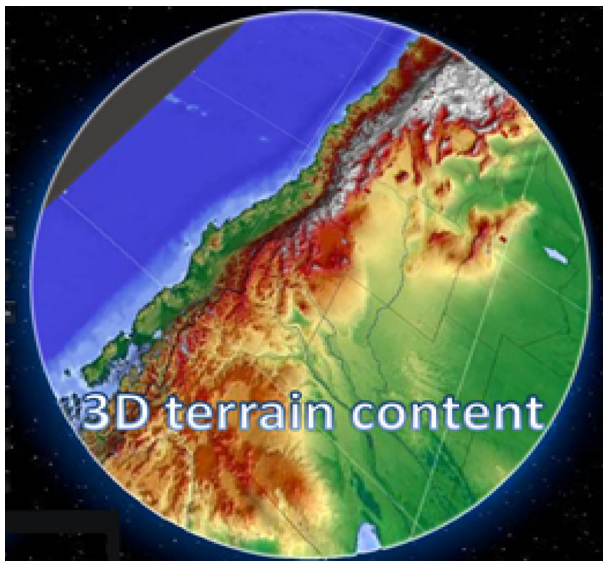


Fig. 6 The zoom in function to see more details of 3-D terrain content

Solar system

DIGS provides an interactive model of solar system (see Fig. 7). Users can point to select any planet, whereby the system provides a detailed description of the selected planet with auditory narrations.

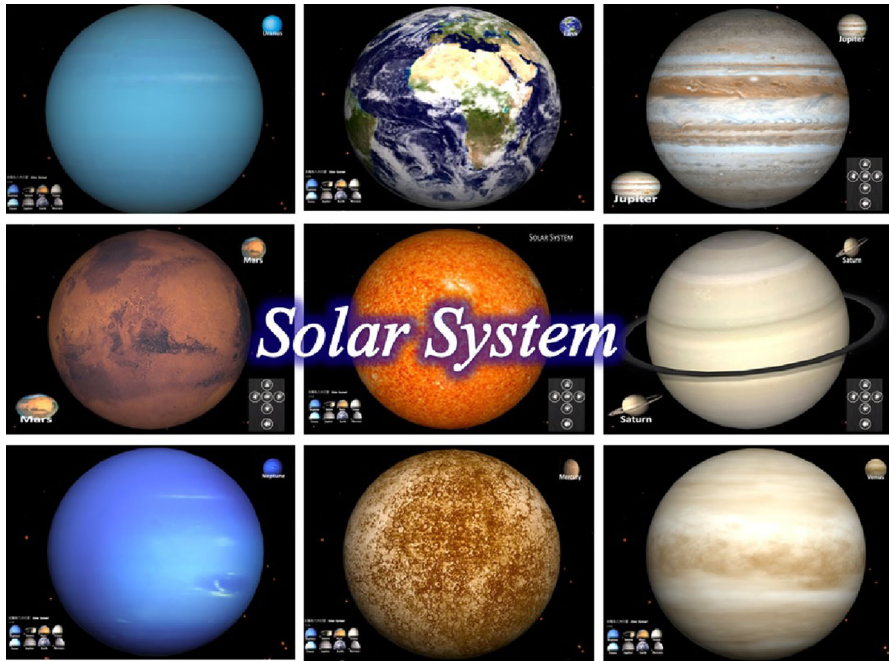


Fig. 7 Screenshot of the DIGS displaying solar system

Earth tectonic system

DIGS describes the Earth tectonic system by visualizing all the components of Earth which are responsible for the movements of the continents, formation of mountains, and ocean basins and occurrence of different natural events such as earthquakes, volcanos, etc. DIGS explains the principles of the Earth's tectonic system (see Fig. 8).

Global carbon-dioxide map

Increased emission of CO_2 is one of the major reasons for global warming (<http://timeforchange.org/CO2-cause-of-global-warming>). DIGS displays average global concentration of carbon dioxide in different parts of the world (see Fig. 9). This visualization helps the students to understand climate change across the globe.

Global ocean temperature

Global ocean temperature influences Earth climate and weather. In other words, ocean temperature is responsible for the natural disasters like hurricanes, typhoons, etc. DIGS provides an interactive visualization of ocean temperature across the globe (see Fig. 10).

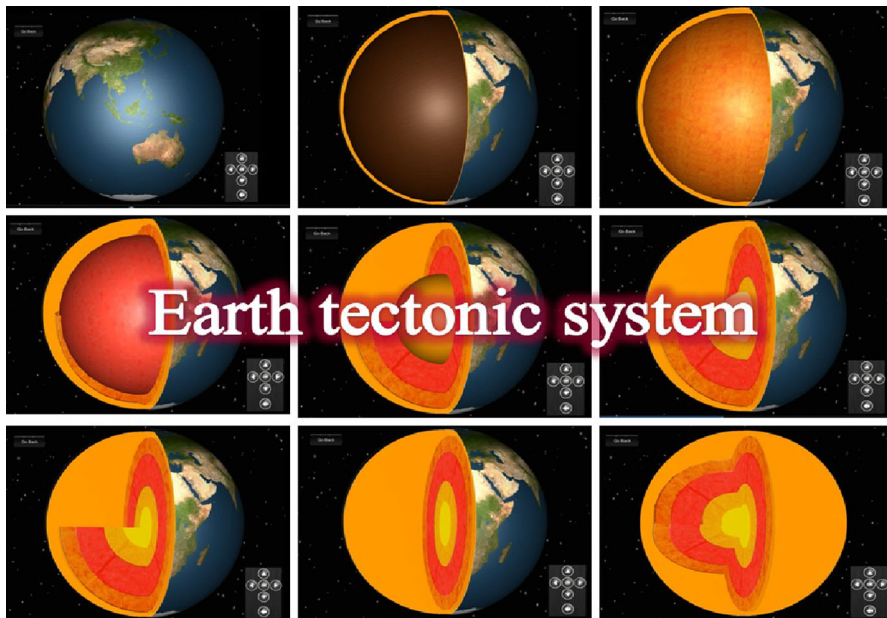


Fig. 8 Screenshot of the DIGS displaying Earth tectonic system

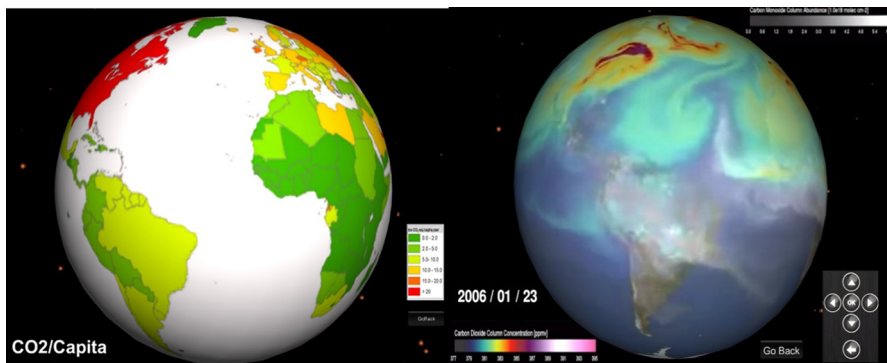


Fig. 9 Screenshot of the DIGS displaying global carbon-dioxide map

Global thundering

Thunder is caused by lightning, which is a result of intense heating and expansion of the air. DIGS shows the number of thundering across the globe based on NASA data (see Fig. 11).

Global hurricane

A hurricane is a cyclonic storm on Earth. DIGS provides interactive information for the better understanding of hurricanes across the globe. Figure 12 displays the visualization of hurricanes created by DIGS.

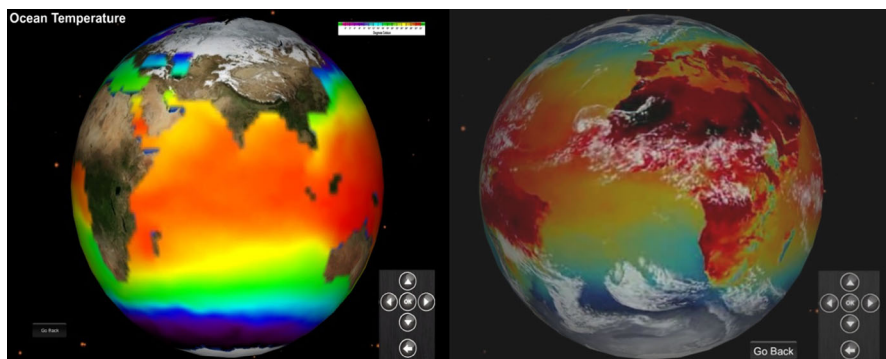


Fig. 10 Screenshot of the DIGS displaying global ocean temperature

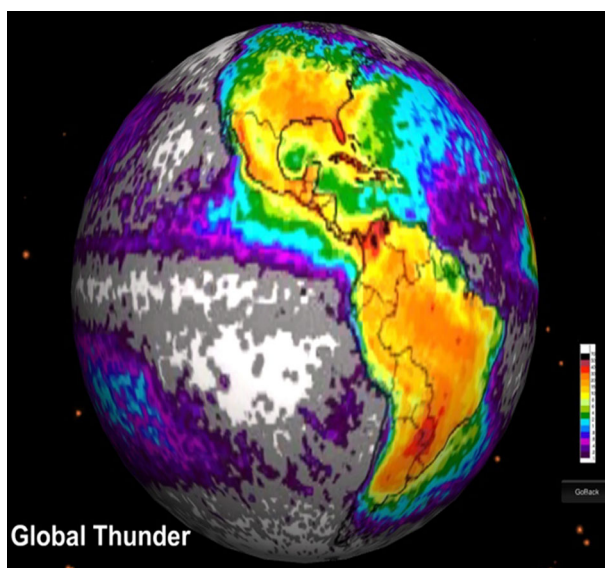


Fig. 11 Screenshot of the DIGS displaying global thundering

Global forest map

Deforestation is one of the major factors contributing to global warming. To protect our environment, understanding the current status of forests across the globe is very important. DIGS presents global forest change over a period (see Fig. 13).

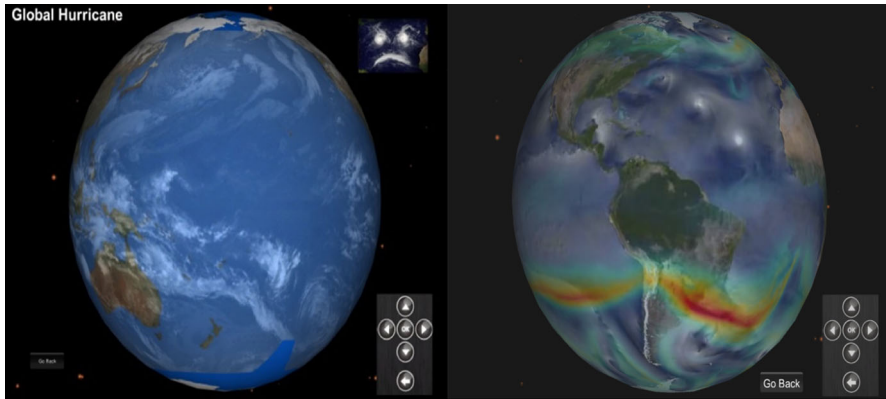


Fig. 12 Screenshot of the DIGS displaying global hurricane

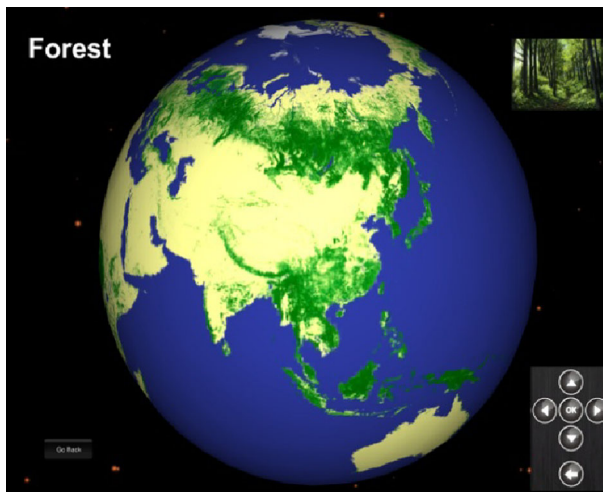


Fig. 13 Screenshot of the DIGS displaying global forest map

Evaluation of DIGS

Research design and sample

The present study employed a quasi-experimental research design, directly assigning participants into groups based randomly on pre-existing classroom settings. A total of 105 (males = 56, females = 49) junior high-school students, aged 14–15 years, were selected from Taiwan and divided into three individual groups of 35 students, including: one control group (CG) and two experimental groups (EG1 and EG2). The CG was instructed using PowerPoint presentation. The other two EGs adopted digital learning system in the class. The only difference between those two experimental classes was that the first EG (EG1) adopted GE in the class while the second EG (EG2) adopted DIGS. The same teacher, using the same course content, taught all three groups. The instructor had previous experience of teaching the course content.

Procedure

This study was conducted over a period of 8 weeks, with four 40-min classes, with one class meeting per week. Therefore, the total duration of classes was 160 min. The objectives of the lesson include: (1) identification of the world distribution of volcanoes and earthquakes, and (2) understanding the Earth layers and tectonic plates.

Before the commencement of the experiment, a pre-test was conducted to assess the level of performance from the students in Earth Science. Test items in pre-test and post-test were isomorphic. The pre-test contained five objective test items and the students were given 5 min to finish the pre-test. Similarly, after the completion of the course, a post-test was administered. The post-test contained 10 objective test items and the students were given 10 min to complete the post-test. For example:

The tectonic plates of Earth are part of Earth's:

- (a) Crust,
- (b) Mantle,
- (c) Lithosphere,
- (d) Asthenosphere.

In the last week of the experiment, a delayed post-test was conducted. The content for both the post-test and delayed post-test was the same. The validity and difficulty level of the test items was done by a panel of subject experts and experienced teachers. Content validity index (CVI) developed by Lawshe (1975) was calculated for both pre-test and post-test. CVI for both pretest and post-test was greater than 0.80, which are acceptable (Polit et al. 2007). The Cronbach's α was 0.80 for pre-test and 0.78 for post-test, which are acceptable.

Data analysis

A one-way mixed design ANOVA was conducted to assess the impact of the three different interventions (CG, EG1, EG2) on participants' learning performance in Earth Science course, across three time periods (pre-test, post-test, delayed post-test). All analyses were conducted using the Statistical Package for the Social Sciences version 21 (SPSS 21). The statistical significance level was set at $p < 0.05$.

Results

As shown in Table 2, all the three groups' pre-test mean score increased in the post-test as well as delayed post-test. Therefore, a one-way mixed design ANOVA was conducted to assess the impact of the three different interventions (CG, EG1, EG2) on participants'

Table 2 Mean and standard deviation for pre-test, post-test scores and delayed post-test scores

Groups	Pre-test			Post-test		Delayed post-test	
	N	Mean	SD	Mean	SD	Mean	SD
CG	35	4.11	.47	6.54	.50	5.94	.23
EG1	35	3.97	.38	7.40	.49	6.97	.29
EG2	35	4.22	.54	8.37	.49	7.94	.33

learning performance in Earth Science course, across three time periods (pre-test, post-test, delayed post-test). Mauchy's sphericity test was used to examine the sphericity assumption. The results showed that there was no violation in sphericity assumption, $W = .98$, $X^2(2) = .197$, $p = .90$. Therefore, the F -value for the main effects and interaction effect did not need correction. As shown in Table 3, the main effect for time was significant, $F(2,204) = 1875.78$, $p < .05$, partial $\eta^2 = 0.94$, which is considered to be a large effect (Cohen 1988). The main effect comparing the three types of intervention was significant, $F(2,102) = 236.33$, $p < .05$, partial $\eta^2 = 0.82$, which is considered to be a large effect (Cohen 1988). In addition, there was significant interaction effect between intervention type and time, $F(2,204) = 53.27$, $p < .05$, partial $\eta^2 = 0.51$, which is considered to be a moderate effect (Cohen 1988).

These results indicated that the achievement scores did follow a different pattern through different times. It could be suggested that students in the different intervention modes performed differently. More specifically, students who were exposed to the DIGS performed better than the other two groups. This situation is further illustrated by Fig. 14.

Discussion and conclusions

In this study, a DIGS was presented for teaching Earth Science courses. DIGS was implemented into a classroom environment for evaluation purposes. This study contributes on both academic and economical view fronts. From the academic fronts of view, empirical results we gathered provide strong support that DIGS is effective and beneficial for the learners for long-term goals. DIGS provides a realistic and captivating 3-D experience to the learners. This resulted in the better performance of the students who participated in DIGS based instruction compared to the other two group. This result is in consistent with Mayer' (2001) CTML theory and Spiro and Jehng's (1990) CFT in that students' learning performance improved by using multiple modes of representations (e.g., graphics, animations, and simulations). Additionally, DIGS presents the informative terrain models that allow the users to adjust and view the displayed images from any angle. This promotes the users to engage with a hands-on-experience resulting in deeper understanding of the concepts presented.

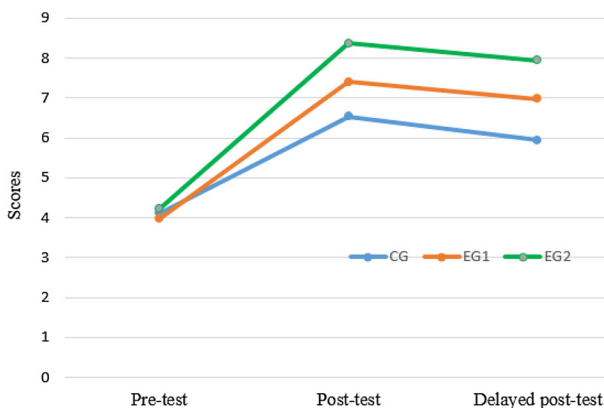


Fig. 14 Comparison of the achievement scores across different times

Table 3 Summary of mixed-design ANOVA

Sources	SS	df	MS	F	p	Partial η^2
Between groups						
Group	91.09	2	45.54	236.33	.000	.82
Error	19.65	102	.193			
Within groups						
Time	680.95	2	340.47	1875.78	.000	.94
Group \times Time	38.67	4	9.67	53.27	.000	.51
Error	37.02	204	.182			

* $p < .05$

The low-cost of the DIGS makes it affordable for developing countries or in rural areas with limited resources. DIGS could be a solution to bridge the wide *digital divide* between countries. The most significant feature of DIGS is that it allows users to interact with its 3-D visualization system. In addition, MBWA function supports the teacher's role as a guide while placing the learner as the focus of teaching–learning process. Therefore, this system seems well suited for teaching and learning Earth Science. Teachers can develop different types of authentic tasks in combination with DIGS to enhance students' critical-thinking skills. DIGS can also be integrated as a tool in the flipped classroom model to make the classroom more interactive. In addition, DIGS can be incorporated in informal learning environments (e.g., museums) to present geographical information visually.

Limitations and future directions for research

The present study has some limitations that should be acknowledged. First, DIGS evaluation was done by using a limited number of test items focusing mainly on *understanding* as domain. Future studies should design test items covering domains like creating, analyzing, applying, etc. Second, observational data (e.g., teacher–student interactions, student–DIGS interaction, etc.) across classroom working with DIGS were not reported. Future studies should collect qualitative data with quantitative to have more in-depth conclusions. Third, we evaluated only students' learning performance for junior high-school students. Future studies should compare the effectiveness of DIGS on students' motivation, satisfaction, and attitude in addition to learning performance, across different grade levels. In addition, the training and support of teachers is worth investigating. Currently, the system is being tested in a rural school in Alabama with minimal training and support of teachers.

We recommend that educators and curriculum designers consider how to effectively integrate 3-D geospatial data lessons so as to connect the classroom with the real world. The future direction of DIGS researchers and developers is focused on creating a database of 3-D map archives as well as a variety of course materials to be used by instructors. In the next step, we are also developing social science contents in addition to science contents and will make it available free for teachers.

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