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Master thesis

EFFECTIVENESS OF 2D AND 3D SYMBOLS ON VIRTUAL GLOBES

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Statement of Authorship

Herewith I declare that I am the sole author of the submitted Master's thesis entitled:

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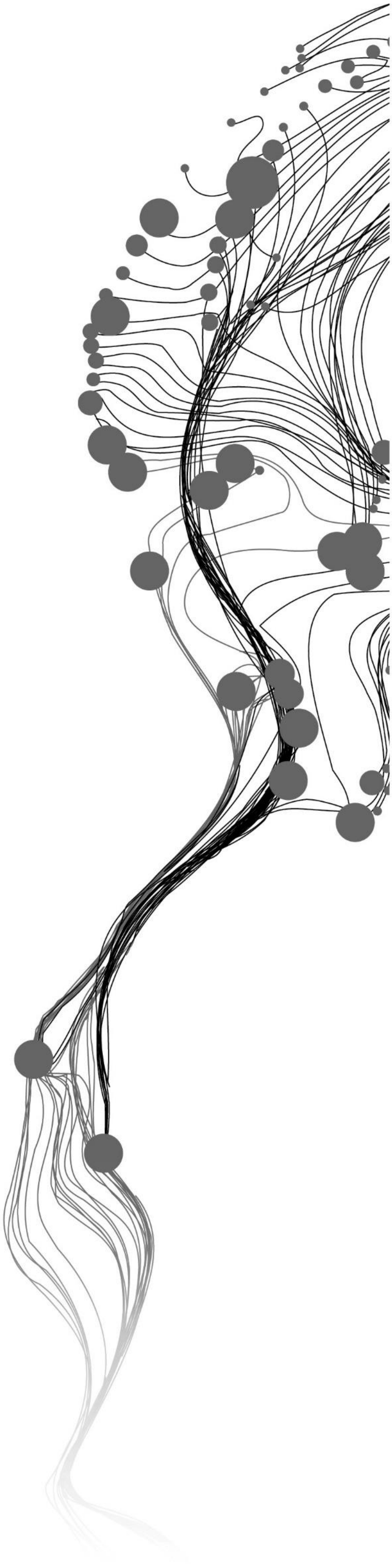

Effectiveness of 2D and 3D Symbols on Virtual Globes

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Enschede, The Netherlands, September, 2023

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
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ABSTRACT

Virtual Globes have been widely used in all research fields to represent geospatial data. Despite the popularity, only a few empirical studies have been conducted to understand how to utilize Virtual Globes for more effective geo-information communication. The overarching research objective for this study is to understand and explore the effectiveness of 3D and 2D symbols on Virtual Globes under different circumstances based on the existing symbolization guidelines. The influencing variables include 1> the different viewing scales of Virtual Globes and 2> the perception of readers with different backgrounds. A user study was conducted with 32 participants filled into cartographer group and non-cartographer group. A Web-based prototype with 3D cylinders and 2D circles is developed by using CesiumJS as a tool for visualization. Shapiro-Wilk test is applied to test the distribution of responses. Wilcoxon test is applied to evaluate the effectiveness of symbol study tasks. Kruskal-Wallis H Test and Post-hoc Dunn's test with a Bonferroni correction are applied for the subjective feeling measurement. The result indicates that 3D cylinders are more effective and preferred than 2D circles at small scales, 2D circles perform badly at all scales but are preferred by both cartographer and non-cartographer users at large scales for a more pleasant aesthetic design. Both user groups are more likely to overestimate the 3D cylinders and underestimate the 2D circles. The likelihood of overestimation and underestimation becomes larger as the zoom level becomes larger. Users' preference and effectiveness of 2D and 3D symbols do not show significant deviation at medium scale. Rather than indicate a specific point as a design guideline, this study proposes the idea that dynamic symbols changing with zoom level could be a better design for Web-based Virtual Globes applications. The specific changing point should always consider the purpose of visualization, the targeting users, the density of the objects, and other influencing factors.

Keywords: Virtual Globes, effectiveness, symbols, zoom scale, CesiumJS

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1. INTRODUCTION

1.1. BACKGROUND AND MOTIVATION

Maps have been a sign of development and progress since the ancient era. Navigators risked their lives to draw nautical charts, marking their travel routes, and the geographical relationship between islands and continents. In past decades, the development of technology, especially internet-based tools, has revolutionized our recognition of the interaction between human and geographic information. There are mainly three essences in this process of change: from static map to dynamic map; from 2D map to 3D virtual geographic environment; from non-interactive to interactive. The new technology, therefore, drives traditional paper maps to a higher level. At the same time, as the technological innovation in the field of remote sensing, the demand for a platform to process and visualize large amounts of earth observation data is rising sharply. For example, as the former vice president of the United States Al Gore (1998) stated, the Landsat program has brought scientists an abundance of information. So, he called for a multi-resolution, three-dimensional representation of the earth to fit vast quantities of geo-referenced data (Craglia et al., 2012).

The first attempt to use computers to simulate the Earth in a virtual environment was conducted in the year of 1960 (Sreevalsan-Nair, 2022). At the end of the last millennium, mature technology made the past impossible ideas come true, including the desktop realization of the concept of the Virtual Globes (VG). A Virtual Globe is a computer-based representation of the real world (Bailey & Chen, 2011). It is a three-dimensional spherical or rounded object made by software with a map rendering the earth on the surface in various scales and projections (Harvey, 2009), and allowing users to interactively pan, zoom, and rotate (Chien & Tan, 2011).

Seeing the successful realization of the Virtual Globes in the desktop environment, scholars set their sights on another virtual environment as well. In 1992, Neal Stephenson described a "live-action" Virtual Globe in his science fiction "Snow Crash" (Bailey & Chen, 2011). This globe presented capable functions that may be beyond the desktop virtual globe. Two years later, Ian Bishop (1994) first proposed the potential use of virtual reality technology in geography. However, the relative technology just started to mature.

At the beginning of the 21st century, several leading companies started to produce Virtual Globes applications, for example, NASA World Wind and EarthViewer. With the official launch of Google Earth in 2005, the Virtual Globe gained extensive attention from the public. The powerful functions of the VG are not only reflected in the direct global-level data visualization but also in serving science. In the next decade, desktop environment VG has been mentioned by 2115 research within various research fields (Liang et al., 2018). Virtual Globes are also popular among non-expert users. It is recognized as a powerful geoinformation communication tool as it supports Volunteered Geographic Information (Blaschke et al., 2012). At the same time, Google Earth makes the VG familiar to virtual reality users. They are being used in more and more GeoWall virtual environment visualization applications with the arrival of commodity head-mounted displays (HMDs) for virtual reality (Yang et al., 2018). Slocum (2013) stated that the wall-sized virtual globe provides a greater sense of immersion than a desktop display.

To this day, the popularity of the Virtual Globes is not decreasing. It is popular in many disciplines, for example, epidemiology (Clarke et al., 2020), and human geography (McDaniel, 2022). Despite that VGs are frequently used in research, there are only very few studies that focus on the theory and empirical study behind VGs and the symbols placed on VGs. This is because most researchers only utilize the

Virtual Globe as a tool in helping data visualization. Although researchers have examined the user preference for point symbols between 2D maps and VGs (Popelka & Dolezalova, 2016), thematic mapping circumstance (White, 2012), the shape and orientation of the symbol (Satriadi et al., 2021). The effectiveness of the symbols placed on desktop VGs for quantitative visualization is still not thoroughly explored (Satriadi et al., 2021). In the desktop virtual environment, there is currently no research focusing on how symbols are performed at different zooming scales. For example, when the researcher places the 3D symbols on the Virtual Globe, it might perform well when the user sees the entire globe. However, the situation might be different when the user zooms in where the virtual globe looks like a flat map. Will 3D symbols also perform well in this case? Or do 2D symbols have a more prominent representation? There is also no research focusing on the difference between readers with different backgrounds perceiving symbols. Will the public users have the same perception as cartographers users who have more experience with symbols and Virtual Globes?

The main objective of this research is to explore and understand the effectiveness of 2D and 3D symbols on Virtual Globes under different circumstances based on existing VG symbol design guidelines.

1.2. RESEARCH OBJECTIVES

The overarching research objective for this study is to explore and understand the effectiveness of 2D and 3D symbols on Virtual Globes based on the existing symbolization guidelines. The effectiveness of the symbols is defined by how accurately and successfully the users can perceive the value represented by the symbols.

This research objective is broken up into three sub-objectives:

RO 1: To explore the usage of 3D and 2D symbols on the Virtual Globe.

RO 2: To design and implement a Virtual Globe prototype in the desktop virtual environment.

RO 3: To evaluate the effectiveness of 2D and 3D symbols under different circumstances.

1.2.1. Research Questions

The three sub-objectives in this study each have three corresponding research questions that should be answered in order to fulfill the main research objective.

RO 1: To explore the usage of 3D and 2D symbols on the Virtual Globe.

1> What are the existing examples of using symbols to represent geographic data on Virtual Globes?

2> What are the visual variables of symbols on a Virtual Globe?

3> How is the design of symbols changing with the development of Virtual Globes in different environments?

RO 2: To design and implement a Virtual Globe prototype in the desktop virtual environment.

4> What platforms are popular and frequently used for building Web-based Virtual Globe applications?

5> How should the 2D and 3D symbols be designed?

6> How to define the concept of "scale" for Virtual Globes?

RO 3: To evaluate the effectiveness and efficiency of 3D and 2D symbols under different circumstances.

7> How are 2D and 3D symbols performing at different zoom scales?

8> How are different user groups perceiving the symbols on Virtual Globes?

1.3. INNOVATION INTENDED

Virtual Globes have been widely used in geospatial-related studies in combination with 3D and 2D symbols to visualize global-range data. However, in most research, the study on VG symbols itself is beyond the scope as researchers only use VG as a tool in helping display information. For desktop environments, researchers (Herman et al., 2018) previously conducted a study comparing user preference between static maps and interactive 3D maps when reading symbols on 3D terrain. Recently researchers have determined 3D symbol and 2D symbol guidelines for virtual globe with real earth model (Satriadi et al., 2021). For the GeoWall virtual reality environment, recently researchers (Yang et al., 2018) have examined whether globes are a better way to show global geographic data or whether traditional flat maps may be better. They also studied which position to place user and globe may work more effectively. There is no research working on understanding how effective the symbols could be at different zoom scales, and there is no research working on understanding how users with different backgrounds perceive symbols on VG.

The overarching research objective for this study is to understand and explore the effectiveness of 3D and 2D symbols on Virtual Globes under different circumstances based on the existing symbolization guidelines. It focuses on 1> three zoom scales of Virtual Globes (small scale, medium scale, large scale; and 2> the perception by different user groups.

The result of this research might be helpful in the future design of Virtual Globe applications for more effective information communication.

1.4. STRUCTURE

This research is divided into six sections. The second section of this thesis will provide a thorough literature review of symbolization and the development of the globe in the virtual environment. Section 3 will begin with the information of the datasets being used for quantitative visualization, and provide the design process of the prototype. Followed by the detailed setup of the user study. The results of two user study groups will be introduced and analyzed with statistical methods in Section 4. Section 5 will include a discussion of the study outcome, design suggestions of symbols on the virtual globe, contribution, and limitations of this research. Finally, the thesis will conclude with a summary of all the findings and possible directions for further exploration in the future.

A link to supplementary materials including JavaScript code, user study setup, post-study questionnaire, and outcome statistics can be found in the Appendix.

2. LITERATURE REVIEW

2.1. DEVELOPMENT OF VIRTUAL GLOBES

Three-dimensional representations have been used to help people understand the world better. The development of the Virtual Globe could be divided into three main periods: 1> the form of the idea; 2> the realization of the virtual globe; 3> the popularity period.

As early as 145 BC, Ancient Greek grammarian, Crates of Mallus, already came up with the idea to represent the earth as a globe (Elvidge & Tuttle, 2008). During the Renaissance era, the terrestrial and celestial tangible globes were considered a matched pair of tools for education in the field of geography and related subjects (Dekker, 2007). At the same time, scholars have made remarkable progress in the invention of map projections (Snyder, 1997). How to project the 3D earth's surface to a 2D flat map without significant projections has been a problem for cartographers for a long time (Yang et al., 2018). During that period, the appearance of many sophisticated map projections partially solved this problem. The production of tangible globes requires not only a higher cost than the traditional paper map, but also larger space for storage as it does not scale (Yang et al. 2018). Because of these reasons, in the following centuries, the use of tangible globes became less popular.

Although the idea was formed early, the Virtual Globes does not have a long history as the limitation of technology development status. Once the internet has been invented, the idea to generate a virtual globe has been coming up. American architect Buckminster Fuller proposed the concept of Geoscope in 1962, which is the earliest attempt to represent the entire planet based on computer technology (Bailey & Chen, 2011). The forerunners that tried to make the Virtual Globe come true also include MIT's Aspen Movie Map multimedia project in the 1970s (Bailey & Chen, 2011). In 1995, the first VG displaying an Earth satellite image was successfully built with Virtual Reality Modelling Language (VRML) by American educator Mark Pesce (Tuttle et al., 2008). At the same time, as the technological innovation in the field of remote sensing, the demand for a platform to process and visualize large amounts of earth observation data is rising sharply. As the former vice president of the United States Al Gore (1998) stated, the Landsat program has brought scientists an abundance of information. So, he called for a multi-resolution, three-dimensional representation of the earth to fit vast quantities of geo-referenced data (Craglia et al., 2012). Driven by demand, the first commercial Virtual Globe that display dynamic earth observation data appeared in 1998 with rotate and zooming functions, which is known as "Planet Earth", later changed to "EarthBrowser" (Bailey & Chen, 2011). The advancing technology of the internet and the high-resolution performance of computers eventually make the virtual globe become a desktop reality.

In the earth stage of the twenty-first century, globes have made an extraordinary comeback. Several "first generation" VG appeared. Seeing the success of "EarthBrowser", several other pioneer companies started to produce VG applications, for example, Keyhole, Inc.; and GeoFusion. In 2001, the Keyhole, Inc. company released the "Earth Viewer". Three years later, it was repackaged with Google and renamed "Google Earth" (Bailey & Chen, 2011). The second vision of "EarthBrowser" was released in 2003. Several new features were added in the update, including hazard display, weather, and real-time datasets (Tuttle et al., 2008). In 2004, another notable virtual globe, NASA World Wind was also released. These applications provide users with a platform where they can "fly" across continents, swooping through cities, and zooming in from space (Nature, 2006).

The Virtual Globe has made huge waves in the academic world after its appearance. However, it was the birth of Google Earth in 2005 brought VG to the public, and it started to catch mass attention. Only one year later, Google Earth has been downloaded over 100 million times (Blaschke et al., 2012). Over the next few years, it was downloaded five times as often (Bailey & Chen, 2011). From 2006 to 2009, there were in total more than 200 representations highlighted the scientific use of VG and other geo-browsers at the annual Fall meeting of the American Geophysical Union (AGU) (Bailey & Chen, 2011). Today, apart from those mentioned above, the prevalent VG applications also include ArcGIS Explorer, Earth3D, Microsoft Virtual Earth, and Skyline Globes.

2.2. APPLICATIONS

The open-source Virtual Globes are a trending topic in geo-visualization. It attracts additional attention compared with traditional 2D maps because of their three-dimensional representation (Blaschke et al., 2012). The powerful functions of the Virtual Globe are not only reflected in direct global-level data visualization on the earth's surface but also in serving science (Ballagh et al., 2011). In the decades after Google Earth was released, the desktop environment Virtual Globe has been mentioned by 2115 researchers across various research fields (Liang et al., 2018). Tuttle and other researchers (2008) proposed seven characteristics of VG that account for its prevalence (Table 1.1). In summary, its interactivity, dynamic state, and the 3D representation of the earth's surface change the way scientists communicate with geoinformation and each other. Moreover, with the mature technology, VG lowered the barrier of cost and provided an opportunity for cheap access (Stensgaard et al., 2009). VG is also popular among non-expert users. It is recognized as a powerful geoinformation communication tool as it supports Volunteered Geographic Information (Blaschke et al., 2012). It allows non-expert users to place and publish their datasets. To this day, the popularity of VG in scientific research is never decreasing.

Table 2.1

Seven reasons for the success of virtual globes

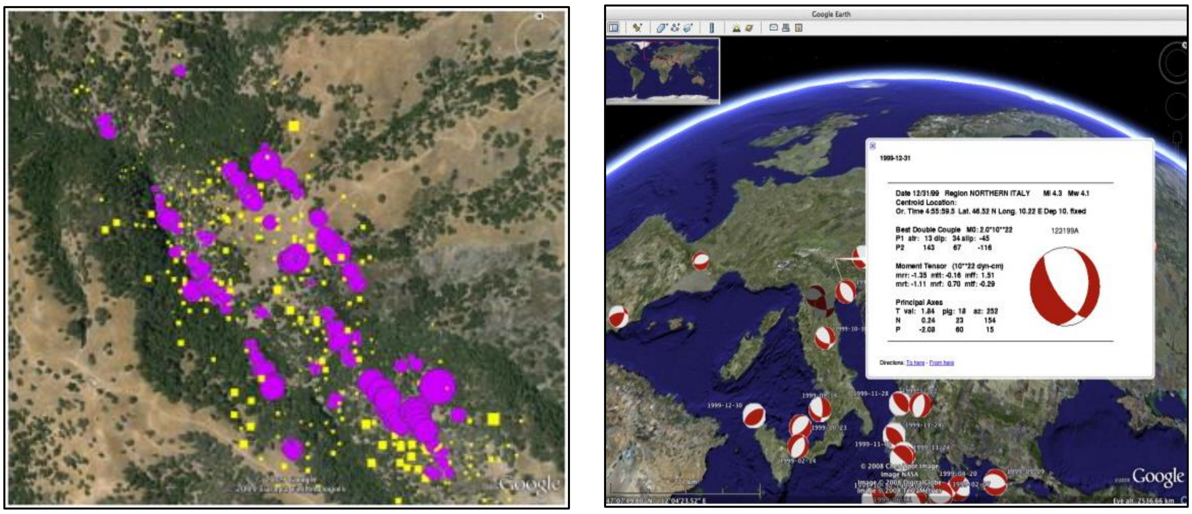
Reason	Description
Pseudo-3D	Allows a person to interact in an environment that they naturally understand.
Transportability	Digital data are easily transported
Scalability	Can be viewed at any scale
Interactivity	Provides an interactive experience for users
Choice of topics	Any number of topics/themes can be presented individually or together and can be changed dynamically
Currency	The data presented can be of any age, including real time
Client-side	Virtual Globes are a client-side technology, which puts the power in the hands of the user

Note. Adapted from Virtual Globes: An Overview of Their History, Uses, and Future Challenges by Tuttle et al. (2018).

Virtual Globes play an important role in the study of Earth Science. It appeared in various research topics, including atmospheric studies, volcanology, hydrology, and seismology (Bailey & Chen, 2011). Researchers use symbols to illustrate movements, quantitative information, and places. It solves the problem that the display windows of traditional commercial software do not fit the curvature of the earth's surface (Chien & Tan, 2011). Turk and other researchers (2011) used 2D circles to simulate the tracks of tropical cyclones on a Virtual Globe. They stated that the VG application has brought an evolution to the visualization of weather data. Webley (2011) placed 2D triangle symbols on Virtual Globe to illustrate the potential hazard of volcanic ash to air traffic. Virtual Globes are frequently used in nature hazard research. Webley et al. (2009) introduced the Puff-Google Maps and Puff predictions of a potential eruption of volcanos. On this interface, 3D triangle shapes with volcano texture are used to represent the location of volcanoes. Chiang and other scholars (2011) use 2D circles and squares with different colors to display real and estimated earthquake activities (Fig. 2.1, left). Postpischl et al. (2011) use 3D beach balls as symbols to represent the earthquake focal on a Virtual Globe. Each beach ball is an earthquake that happened in history, with all the information available (Fig. 2.1, right). In similar research, Paor and Whitmeyer (2011) also use the 3D "beach balls" to represent focal mechanisms. These beach balls are placed above the VG and are color-coded to represent hypocentre depth. In 2014, Jones and other researchers (2014) proposed a five-star visualization method quality recommender system. They use 2D five-star shapes with different textures to represent different qualities.

Figure 2.1

Application of Virtual Globes



Note. (left) Use of points to highlight earthquake activity in an area of Northern California as generated by HypoDD program, showing earthquake hypocenters as initial estimates (circles) and computed (squares) with test data provided by program web site. From Geo-visualization Fortran library by Chiang et al. (2011). (Right) D beach-ball representation of focal mechanisms is georeferenced in Google Earth. From Standardization of seismic tomographic models and earthquake focal mechanisms data sets based on web technologies, visualization with keyhole markup language by Postpischl et al. (2011).

As early as the 14th century, tangible globes have been used as a tool in teaching geography and related subjects (Dekker, 2007). The usage of Virtual Globes in education is remarkable. The VG is used to help students understand the basic elements of 3D maps such as latitude, and longitude (Tuttle et al., 2008). Weber et al. (2010) mentioned the Swiss World Atlas while developing a new gaming method for cartography navigation. In the atlas, 2D square symbols are used to represent the location of the cities.

The use of symbols on Virtual Globes does not have significant change through its development. In recent research, Vorobev et al. (2020) placed red dots on a VG and combined them with a dashboard to indicate the locations of magnetic observatories. Similar applications can also be seen in the field of epidemiology. Brugger and Rubel (2023) utilize a virtual globe to visualize the geographic distribution of ticks. They use 2D star primitive to represent the city location. They stated that the use of VG makes it easier for laymen to read spatial information.

2.3. SYMBOL VISUALIZATION

Symbols play an important role in the field of cartography. The basic principle of cartographic design is to transfer the collected geographic information into a multi-dimensional representation (Garlandini & Fabrikant, 2009). The leading cartographer Jacques Berti (1983) stated in his book "Semiology of Graphics: Diagrams, Networks, Maps" that each cartographic representation is supported by a system of signs (symbols). The isolated data cannot tell a convincing story. Therefore, symbols are also one of the elements that decide the difference between an ordinary map and a persuasive map (Deluca & Bonsal, 2017).

The process of how features on a map are visualized is defined as the term symbolization (Deluca & Bonsal, 2017). Deluca and Bonsal stated that it is important for cartographers to constantly consider this process to help map readers understand the maps more effectively and efficiently. In the book "Thematic Cartography and Geovisualization", Slocum and other researchers (2013) proposed three aspects that need to be considered for symbolization. The first aspect is the nature of the geographic phenomenon. There are several different ways to consider this aspect. One way is to classify the data as discrete or continuous (Slocum et al., 2013). Another way is to consider whether the data is points, lines, polygons, or volumes (Slocum et al., 2013). The second aspect is the level of measurement, which indicates whether the data is nominal, ordinal, interval, or ratio (Slocum et al., 2013). The third aspect is the visual variables of the symbols that can be considered in visualization.

Visual Variables refers to the various perceived difference in symbols that are used for spatial visualization (Slocum et al., 2013). Cartographers modify the appearance of symbols by modifying the visual variables. In this way, different types of information could be received and communicated by readers. This concept was first developed by French Cartographer Jacques Bertin(1983) in 1967 and later translated into English. He proposed seven visual variables including two planar variables and five "retinal" variables (size, color value, color hue, shape, and orientation) (Garlandini & Fabrikant, 2009). In the following years, it has been discussed by many other researchers (MacEachren, 1994). Cartographers have later extended the visual variables with different contents (Tyner, 2010).

2.3.1. Visual Variables of 2D Symbols

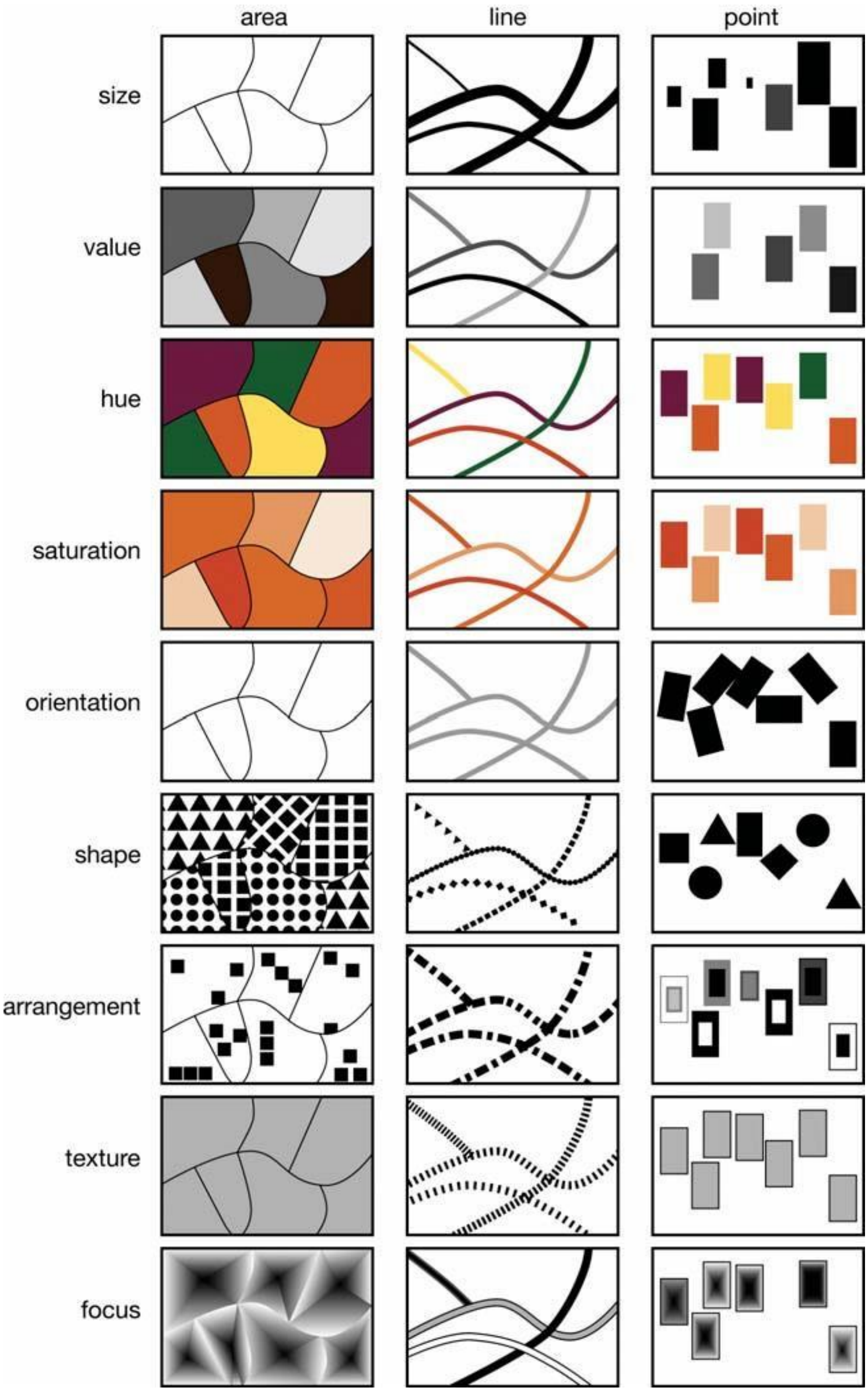
MacEachren extended Bertin's visual variables theory and introduced those virtual variables for points, lines, and polygons features (Figure 2.2). In this figure, each row corresponds to one visual variable, each column corresponds to one nature of Geographic phenomenon. Among these visual variables, size and value are the most common type.

Size is one of the visual variables that have been frequently used for quantitative data visualization. The size of the symbols refers to the amount of space occupied by the map symbol (Roth, 2016). Large sizes are often understood to represent something of high value or importance, while small sizes represent low or less important values. Symbols of smaller size usually are used to represent lower value or less important objects, while symbols of larger size usually stand for higher value or higher importance (Deluca & Bonsal, 2017). There are two different visualization ways to utilize size (Slocum et al., 2013). One way is to change the size of the entire symbols. Another way is to change the texture or markers that make up the symbols.

The value of symbols is also popularly considered. The value describes the relative amount of energy emitted or reflected by the map symbol (Roth, 2016). It refers to the degree of lightness or darkness of a particular hue (Deluca & Bonsal, 2017). The variation in hue is the difference in colors. This accounts for the shading effect in symbols. The difference in lightness and darkness also creates figure-ground relationships of symbols (Roth, 2016). This refers to the phenomenon that the two sides of color rise the visual attention of each other.

Apart from the size and value, the shape of the symbols. Shape refers to the external form of the sign vehicle (Roth, 2016). Shapes have been commonly used in qualitative visualization with various forms and outlines to represent different characters. In quantitative visualization, cartographers also use uniform shapes to help visualization. Many researchers conducted a study on the effectiveness and efficiency of the shape of symbols in various environments, for example, on a virtual globe.

Figure 2.2
2D visual variables



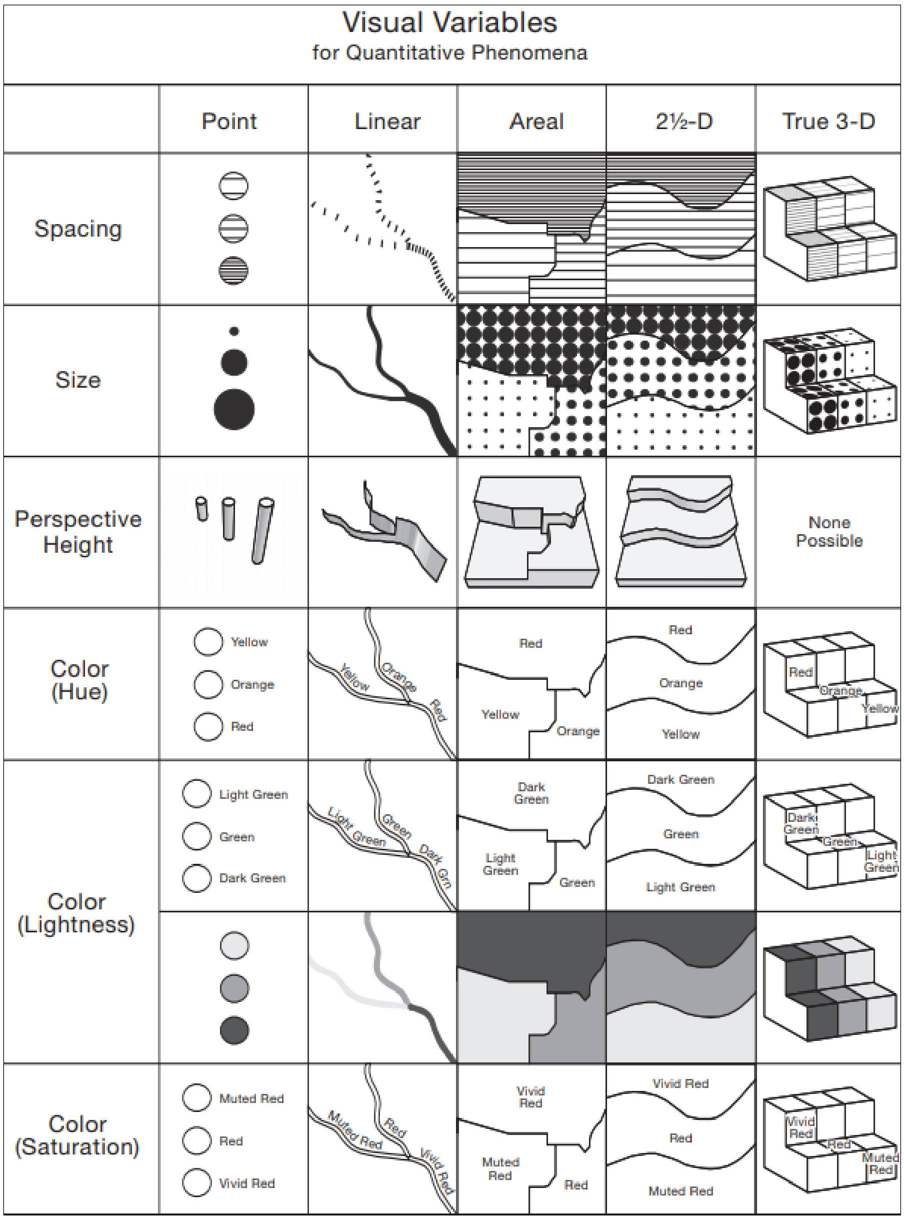
Note. Bertin's graphic primitives, extended from seven to ten variables. Source: MacEachren, (1994). from Visualization in Geographical Information Systems, Hearnshaw H.M. and Unwin D.J. (eds), Plate B (P. Longley, 2005).

2.3.2. Visual Variables of 3D Symbols

3D symbols are 2D symbols with extended properties that bring more realism to the map (ArcGIS Online). As 3D symbols on a 2D screen provide height information as well, cartographers also consider this case as 3D visualization (Liu et al., 2017). They are widely used in geography and related fields nowadays. Mete and other scholars (2018) stated that the use of 3D data visualization creates a better situation for decision-making, planning, or solving problems. Well-established guidance is important to ensure the 3D symbols can be efficiently and effectively perceived by the map audience. In previous research, scholars have conducted thorough studies on 2D visual variables and their performance. Many researchers have also attempted to improve 3D visualization (Suárez et al., 2015).

Figure 2.3

Visual variables for quantitative phenomena



Note. Captured from Thematic Cartography and Geovisualization by Slocum et al. (2013).

However, the study on 3D visual variables is still defective. In recent research, Vetter and Olberding (2022) stated that cartographers always need extra and special considerations when using symbols in the 3D environment. Slocum and other scholars (2013) suggested visual variables for quantitative and qualitative visualization based on MacEachren's extension. Apart from points, lines, and polygons, they also include the 2.5D and true 3D situations (Figure 2.3).

Many researchers have proposed that the visual variables of 3D symbols might perform differently from flat 2D symbols. This is because the environment contains other elements that affect the reader's perception, for example, the depth cue could affect the size (Hatfield, 2014) and shape (Li & Pizlo, 2011). Häberling (2005) has proposed several aspects that should be considered for 3D map design, including symbolization (Table 2.2). One of the first attempts to define and evaluate 3D visual variables was done by Häberling (2003) in the project of the ETH Cartography group. In his study, he considered visualization aspects, including the inclination angle of the direction, and the viewing distance, the horizontal lighting direction, sky structure, and haze density.

Table 2.2
Design aspect of symbolization

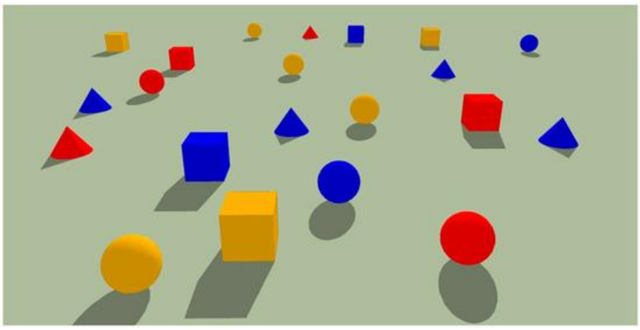
	Aspects
Symbolization	Graphic appearance
	Special graphic aspects
	Textures
	Text objects
	Object animation

Note. Adapted from Cartographic design principles for 3D maps: A contribution to cartographic theory by Häberling, C. (2005).

Semmo (2012) stated that the visual variables need to fit the specific tasks for effective and efficient information communication. In later research, Semmo (2012) also concluded various aspects of 3D visual variables design, including colorization, object textures, edge enhancement of 3D objects, transparency of 3D objects, and real-time rendering.

Liu and other researchers (2017) have used eye-tracking technology to explore visual guidance for the design of 3D symbols. They analyzed the shape, hue, and size; and, the visual constancy of shape, size, color, and saturation (Fig. 2.4). Based on the result, they found that the hue and shape perform better as visual guidance. Size, which is considered the most effective 2D visual variable, is limited in the 3D environment. Liu et al. also proposed that shape and saturation have better efficiency, while size performs worse.

Figure 2.4
Investigate shape guidance



Note. The participants were asked to find all the spheres. From Using Eye Tracking to Explore the Guidance and Constancy of Visual Variables in 3D Visualization by Liu et al. (2017).

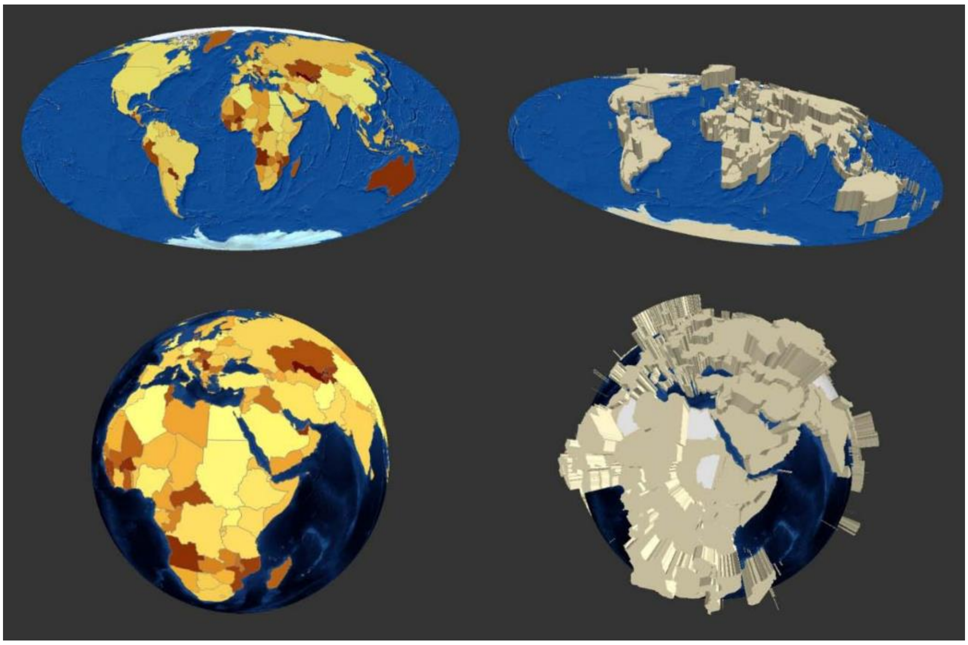
2.3.3. Symbols on Virtual Globes

Everything on a map is something in the real world represented by symbols. The symbols on VG are the same. After the launch of Google Earth, the virtual globe attracts mass attention from both academic and non-academic sides. Researchers see the virtual globe as a tool in helping visualize their research topic and results. They place 2D or 3D symbols on VG to represent quantitative data. A "rule" to guide cartographers in designing these symbols would help readers receive the information in a faster and more accurate way. Therefore, map makers must consider symbolization constantly to help people read the map effectively and efficiently (Deluca & Bonsal, 2017). However, the study of those symbols placed on VG has been rarely conducted. The high applicability of virtual globes makes researchers overlook the empirical study of combing virtual globes and symbols. This contains the aspect of the effectiveness and efficiency of symbols. So far, little empirical evidence could be used as support for designing (Satriadi et al., 2021).

A similar challenge at an early stage is the exploration of the effectiveness and efficiency of the virtual globe to traditional 2D maps, especially for thematic mapping. As this is not the original function of the virtual globe, the evaluation only appeared after the function surfaced (Häberling et al., 2008). One of the studies is conducted by Travis Maclean White (2012). He compared the effectiveness of a virtual globe for thematic mapping to traditional 2D maps. In his user study, he includes four visualization prototypes: 1> choropleth flat map; 2> choropleth globe; 3> prism flat map; 4> prism globe (Fig. 2.5). He summarized the statistics and then gave a conclusion that there is no significant preference between VG and flat maps. In later research, Popelka and Dolezalova (2016) used eye-tracking technology to compare the performance of point symbols on 2D flat maps and VG. In their user study, participants were asked to complete object size determination. They then suggested that the distortion confused users and make the symbols less effective and less efficient.

Figure 2.5

Examples of the experiment maps



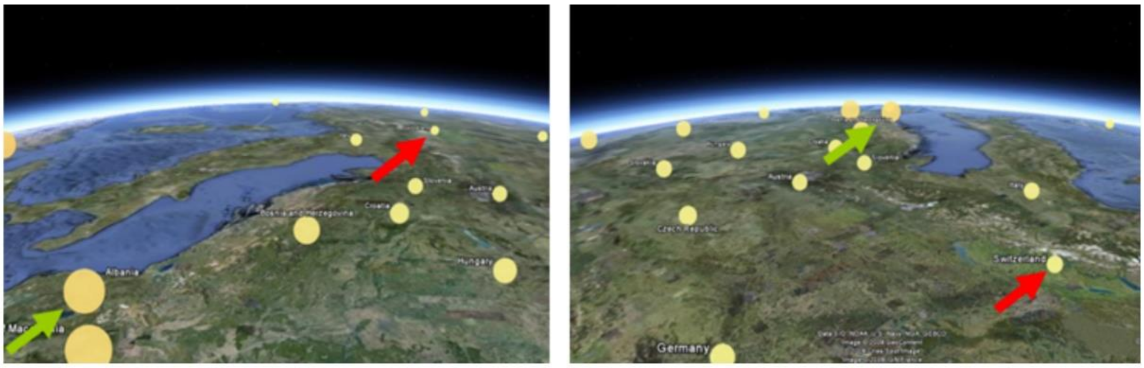
Note. Clockwise from top-left: choropleth flat map, prismatic flat map, prismatic virtual globe, choropleth virtual globe. Scale is not consistent between the flat maps and virtual globes. From Evaluating the Effectiveness of Thematic Mapping on Virtual Globes by Travis Maclean White (2012).

It has been a long time since cartographers utilized cubes, spheres, or more complex objects for point symbols on VG (Popelka & Dolezalova, 2016). Former cartographers have dropped different ideas on the design of symbols in a virtual globe environment. Shepherd (2008) proposes that the traditional cartographic design principles do not fit for VG environment, while Fabrikant (2005) stated that they may partially apply.

To help understand the symbol design, various graphic studies have been conducted. In the chapter on "Spatial Information Theory", Garlandini and Fabrikant (2009) proposed an empirical evaluation of the effectiveness and efficiency of visual variables on 2D maps. Their study covered the discussion of the size of the symbols, the color hue, the color value, and the orientation of the symbols. By testing thirty-two visualizations, they concluded that "size" is the most effective and relatively more efficient visual variable. Bleisch (2011) introduced two examples to explain why cartographers are questioning the design of 2D quantitative visualization in the virtual environment (Fig 2.6). Bleisch and other scholars (2008) have examined the effectiveness of 2D bar billboards for quantitative data. They added the reference grid to help users read. Their result showed the effectiveness of this visualization for simple tasks. They also assumed that graphics, for example, circles would be less effective because with one dimension these symbols do not provide depth cue.

Figure 2.6

Children under five mortality rates per country in 2005

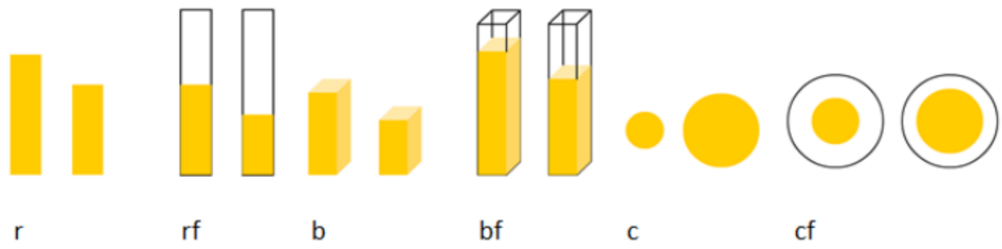


Note. Circular 2D symbols to show children under five mortality rates per country in 2005 looked at from two different viewpoints (red arrow: Switzerland; green arrow: Albania). From Toward Appropriate Representations of Quantitative Data in Virtual Environments by Susanne Bleisch (2011).

Bleisch (2011) also claimed that not only the size of the 3D symbols but also the depth cue size gradient needs to be considered when using 3D symbols in the virtual environment. With testing twenty prototypes (Fig. 2.7), Bleisch (2011) suggested the more effectiveness of 3D bars beyond 2D bars, and 2D circles were the least accurate but not as bad as expected. In the later research, Bleisch and other scholars (2015) also found that 2D bars do not perform differently between 2D flat maps and 3D terrain maps.

Figure 2.7

Quantitative symbols

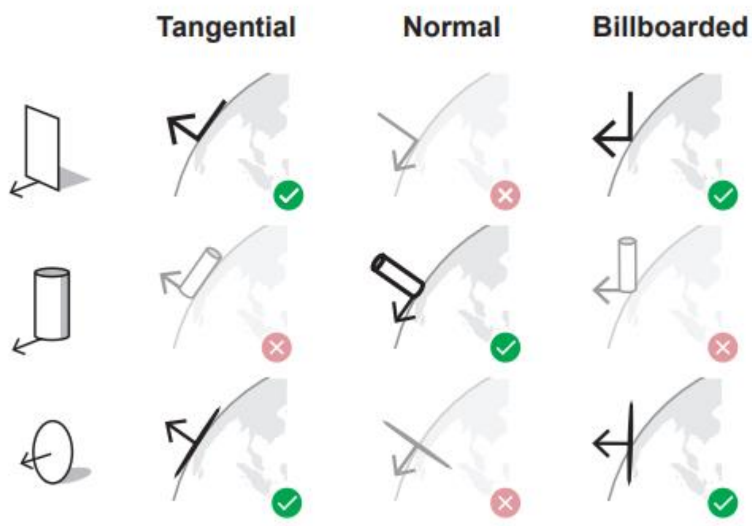


Note. Quantitative symbols (named r, rf, b, bf, c and cf) as used in the experiment. 2D bars (r), 2D bars with reference frame (rf), 3D bars (b), 3D bars with reference frame (bf), 2D circles (c) and 2D circles with reference frame (cf). From Toward Appropriate Representations of Quantitative Data in Virtual Environments by Susanne Bleisch (2011).

For discrete values, it was suggested that value-proportional symbols could best visualize the geographic phenomenon (Slocum et al., 2013). Based on the former finding, Satriadi and other researchers (2021) focused on quantitative data visualization on VG. Apart from the commonly considered elements and primitives, they explored the effectiveness and efficiency of symbols when considering the orientation of symbols (Figure 2.8). Based on their user study result, they came up with a new prototype for Virtual Globe visualization that combined bar charts and VG. Satriadi and other scholars (2021) proposed eight design implications in their discussion. Regarding effectiveness, they suggest that the tangential circles were the least effective idiom while the length-proportional design perform better. Regarding on efficiency, they proposed that the length-proportional design performs worse than the area-proportional visualisation. Based on the result, they suggest billboarded Circles have the best performance in efficiency while Normal Bars perform the worst. They also found that enlarging the relative size difference between objects helps improve the accuracy.

Figure 2.8

Visualisation idioms



Note. Visualisation idioms for quantitative data visualisation on globes. Idioms with a cross are discarded. From Quantitative Data Visualisation on Virtual Globes by Satriadi et al. (2021).

2.4. VIRTUAL REALITY

Nowadays, rapidly developed technology brought us abundant information. The datasets are growing not only in size but also in complexity. At the same time, researchers have never stopped the exploration of new methods to help people communicate with rich geo-information. In 1992, Neal Stephenson described a "live-action" virtual globe in his science fiction "Snow Crash" (Bailey & Chen, 2011). This globe presented capable functions that may be beyond the desktop Virtual Globe. Two years later, Ian Bishop (1994) first proposed the potential use of "virtual reality" technology in geography. At the end of the millennium, former American Vice President Al Gore gave his "Digital Earth" speech in California. Al Gore (1998) called for "Virtual Globes" to represent abundant multi-resolution and three-dimensional data. He proposed a vision that was far beyond the concept of a Virtual Globe at that time, which used a heads-up display and "glove" to navigate the Digital Earth.

Virtual Reality (VR) is an advanced technology that simulates a realistic environment (Zheng et al., 1998). It utilizes a head-mounted display (HMD) to let users experience realistic simulations. As the speed and quality of internet connection are improving (Tuttle et al., 2008), the immersive environment has been known to larger populations. In the early stage, the idea of Virtual Reality is to simulate the tangible real world (Slocum et al., 2013). Figure 2.9 is an example of this idea. It is a virtual version of a real antique tangible globe stored at the National Maritime Museum in London (The Map Room, 2020). During the COVID pandemic, people can view, navigate, and interact with this treasure in VR even when the museum is closed. Slocum et al. (2013) introduced the idea of GeoWall. It is a specific form of wall-sized display to create a Virtual Environment for Geography interests (Slocum et al., 2013).

Figure 2.9

A Virtual 16th-Century Globe

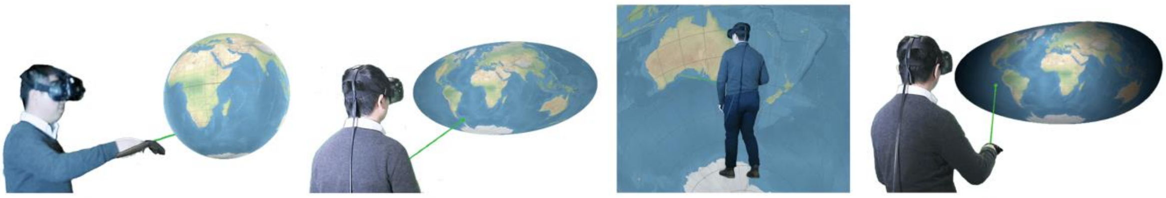
Note. Captured from The Map Room, (2020)

Because of the barrier difference between computer and VR equipment, the prevalence of VR technology in Cartography is going slower than desktop VG. Yang and other researchers (2018) evaluated four different viewpoints of VG and flat maps in a VR environment (Fig. 2.10), including exocentric globe (a), flat map (b), egocentric globe (c), and curved map (d). They designed three tasks in the user study, including distance comparison, direction estimation, and area comparison. Yang et al. (2018) proposed that the different visualizations have different performances regarding different tasks, but the exocentric globe performed best in effectiveness overall while the egocentric globe performed the worst. Kloiber et al. (2022) developed a prototype for country-shaped quantitative data visualization on VG in a VR environment (Fig. 2.11). They stated that visualization methods provide access to investigate global patterns of behavior. In future research, they plan to evaluate the effectiveness of this visualization and investigate the difference in spatial perception in VR environments and desktop environments.

The study of symbol visualizations in VR environments only appeared in recent years. Arjun and other researchers (2021) examined and evaluated the 3D visual variables for 3D graphs. They compared variables including size, orientation, opacity, colour, and shape. Their result showed that the size and colour perform better regarding effectiveness.

Figure 2.10

Four viewpoints interactive visualisations for geographic data in Virtual Reality (VR)



(a) Exocentric globe (b) Flat map (c) Egocentric globe (d) Curved map

Note. Captured from Maps and Globes in Virtual Reality by Yang et al. (2018)

Figure 2.11

3D globes currently displaying COVID infection numbers via country elevation and colour

Note. Left/Middle: Two consecutive days where we can see the different reporting interval of countries. Right: Zoomed-in view. From Immersive Analytics for Spatio-Temporal Data on a Virtual Globe: Prototype and Emerging Research Challenges by Kloiber et al. (2022).

2.5. CESIUM 3D PLATFORM

Benefiting from the globalization and evolution of the Internet, access to geographic information has become significantly easier than in the past. Advanced technology drives the emergence of web-based applications. This benefits the public users from three aspects. Firstly, web-based applications made it possible to visualize, store, create, and share geospatial data in a low-cost condition, where only a web browser and internet connection are needed. Secondly, it allows users to access the information twenty-four hours a day, and seven days a week (Mete & Yomralioglu, 2018). Finally, users could access, edit, and use the data concurrently on different platforms (Mete & Yomralioglu, 2018).

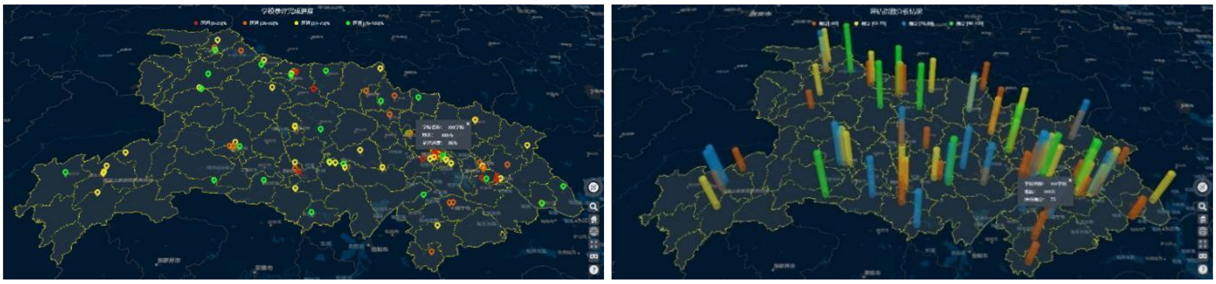
The open-source 3D virtual globes aim to improve the geo-visualization provided by standard web services or with proprietary formats (Staso et al., 2016). Since the release of Google Earth in 2005, creating KML overlays has been the most common way to visualize spatial information on a web-based Virtual Globe (Sandvik, 2008). The Google Earth plug-in provided a simple way that made it enormously prevalent for many years. However, the company stopped this service at the end of 2015 because of security issues (Munasingh et al., 2017).

Along with the progress, the diversity of web-based applications for spatial information visualization has also broadened. Several JavaScript-based Virtual Globe libraries and APIs (Application Programming Interfaces) were developed based on new technology, WebGL and HTML5 (Gede, 2018). JavaScript is a popular programming language that enables users to create interactive and dynamic web pages (Mete & Yomralioglu, 2018). There are many map libraries currently available for rendering 3D graphics information on the web platform. For example, Cesium JS, ArcGIS API for JS, Vizicities, OSM Buildings GL, WebGL Earth JS API, Nasa Java World Wind, and many other libraries (Mete & Yomralioglu, 2018). The remarkable advantage of these libraries is that no other software, licenses, or plug-in is required for web visualization (Mete & Yomralioglu, 2018). Since they are based on JavaScript, they are supported by all the prevalent web browsers. These frameworks have enabled more complicated 3D visualizations on the web and enhanced performance (Kramer and Gutbell, 2015).

By comparing the advantages and limitations of all the new products, Cesium API has stood out and is recommended by researchers (Cozzi, 2013). Cesium offers rich documentation and wider functionalities (Gede, 2018). Its application can be seen in recent studies extensively (Wu et al., 2021) (Figure 2.12).

Figure 2.12

Visualization example with Cesium

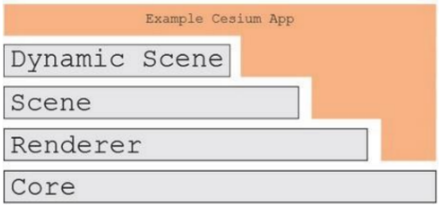


Note. (Left) 3D visualization of the completion progress of participating schools. (Right) 3D visualization of the distribution of evaluation indexes. From Work-in-Progress—Design Method of a Real-Time Monitoring System for ICT Evaluation Process in Education Based on CesiumJS 3D Visualization, by Wu et al. (2021).

Cesium is made up of three assemblies (Figure 2.13): 1> Core.dll, which is the lowest layer that contains the basic functions such as transformation and calculation. 2> Render.dll, which is the "middle layer" that provides functions such as shader, texture. 3> Scence.dll, which provides high-level functions including the creation of geometry (Chaturvedi et al, 2015).

Figure 2.13

Three layers of Cesium



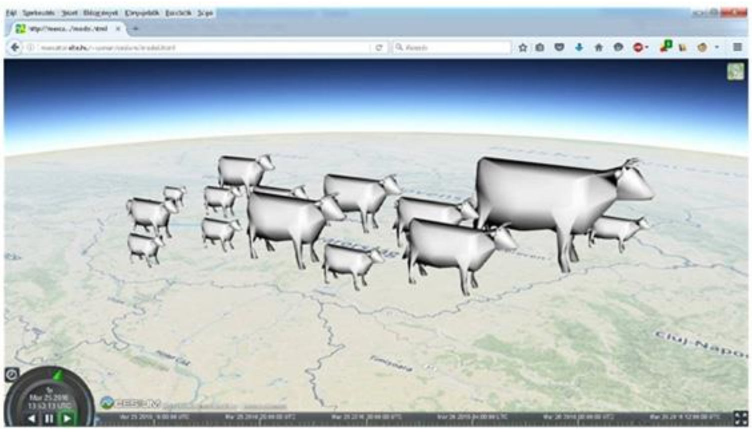
Note. From Web-based Exploration of and Interaction with Large and Deeply Structured Semantic 3D City Models using HTML5 and WebGL, by Chaturvedi et al. (2015)

Cesium has several platforms for different software and usage. CesiumJS is an open-source JavaScript library for creating 3D virtual globes and web applications with high precision and quality (Cesium, 2023). It originated from a virtual globe project developed by Analytical Graphics, Inc. (AGI) in 2011 (Hu et al., 2018). It requires simple codes to embed VG into HTML and utilize WebGL for acceleration. Meanwhile, it supports various data formats for rendering (Buyukdemircioglu & Kocaman, 2021).

The powerful functions made Cesium become one of the best substitute platforms after Google Earth stopped the web service. Several well-known types of research that use CesiumJS for visualization are currently under development, for example, the NASA Global Precipitation Measurement Program (Buck et al., 2021). The platform provides users with the settings for cameras, shades, lights, and many other tools. Users could manage the color and size of the geometry easily by combining it with Three.js. The interoperability of the data provided allows user to integrate their projects from different platforms easily (Mete & Yomralioglu, 2018). Cesium also provides the time-dynamic function for 4D visualization (Chaturvedi et al., 2015), which refers to spatial three dimensions and time dimension. Gede (2018) provided an example using a scaled model that changes with multi-timestamps for temporal quantitative data visualization (Figure 2.14). Besides the static 4D, animation could also be generated. With the tool "Terrain Builder", it is also possible to provide multi-resolution worldwide terrain without using any plug-in (Staso et al., 2016).

Figure 2.14

Scaled 3D models for displaying quantitative data



Note. From Using Cesium for 3D Thematic Visualisations on the Web by Gede (2018).

3. METHODOLOGY

This section will focus on the relevant dataset, prototype design, and the user study being conducted. As mentioned in the first section, the overarching research objective is to explore and understand the effectiveness of 2D and 3D symbols on Virtual Globes. To explore the performance of symbols for visualization, a quantitative dataset should be selected for the study. As zooming level is part of the main research objective, the dataset should contain records for comparison at different scales. The study of the insight of the data is not part of the purpose. In this case, datasets focus on any topics that contain quantitative information that would fit. The study could be divided into two processes: Designing and implementing the prototype in a virtual environment and user study. The Cesium 3D platform and JavaScript are used for creating the VG in the desktop environment. Qualtrics website is used for creating the survey for study tasks and post-study questionnaires. Prototype is displayed on a laptop while study tasks are displayed on another device. The users are divided into two groups: the cartographer group and the non-cartographer group. Details will be explained in the following sub-sections.

3.1. DATA

3.1.1. Data Source

The quantitative data used for visualization in this study is the "World Cities Database" from Simplemaps website (Figure 3.1). As the website introduced, this dataset contains four characteristics:

1> Up-to-date: The last update of this dataset was in March, 2023.

2> Comprehensive: The datasets contain over four million prominent (large, capital) cities from all the countries over the world.

3> Accurate: The data records, including latitude and longitude are from official sources.

4> Simple: The dataset can be download in free csv version.

Each record contains the following information: the name of the city; the name of the country it belongs to; ASCII string; latitude; longitude; alpha-2 iso code; alpha-3 iso code; the name of the highest-level administration region of the city town; population; population density. Figure 15 displays the geographic location of cities contained in the basic (free) version. The provided statistics are from authoritative sources. The U.S. cities data comes from the U.S. Census Bureau and the U.S. Geological Survey. All non-U.S. countries cities comes from the National Geospatial-Intelligence Agency.

The main reason to choose this dataset is because it contains records at both the global level and city level. Exploring the effectiveness of symbols at different zoom scales is one objective of this study. Therefore, it is necessary to ensure that there will be symbols for comparison after zooming to a certain extent.

Figure 3.1
Basic Database Cities

From "World Cities Database" by Simplemaps, https://simplemaps.com/data/world-cities.

3.1.2. Data Pre-Process

As the dataset contains over four million records for prominent cities, to reduce the interference of overmuch data records only selected cities will be used in the user study. A population threshold, where the population is larger than three million is set to filter the data records to be used. This is mainly considering two aspects: 1> Too many data records will affect the visual effects of users. Gede (2018) stated that although the 3D web platform provides unlimited visualization of visual variables, cartographers need to consider the information loss caused by too many objects placed on VG. 2> Overmuch geometry in the prototype might cause a slight negative effect on the smoothness of loading.

Besides, a fetchData( ) function is applied to the world cities CSV dataset. This function identifies the necessary information, and extracts and reads the column for the prototype. In this study, the longitude, latitude, population, and name of the cities are selected for creating the point data. The advantage of this function is that it is not affected by the changing of the origin dataset, and omits the process to manually edit the filter inside the data files. The codes are written in Notepad++.

3.2. PROTOTYPE DESIGN

3.2.1. Concept of “Scale” for Virtual Globe

Scale is an essential concept in all fields of science, especially for cartography, geography, and other disciplines that deal with geospatial data (Slocum et al., 2013). Researchers study the scale from human to globe in the field of geography and cartography. The term “scale” also has different divisions in these two fields. In cartography, the traditional 2D map scale is defined as the ratio of distance measured on the map to the actual distance in the real world (ICA, 1973). In 2D maps, the selection of map size and map scales are recognized as very important considerations as they influence the appearance of the map and the communication of geo-information. The map scales are usually defined and divided into three levels:

1> Large scale maps: Scale larger than 1:25 000

2> Medium scale maps: 1:50 000 to 1:100 000

3> Small scale maps: Scale less than 1:200 000

The larger scale maps show less area, while the smaller scale maps show larger area. A larger scale map usually shows more details of the study region while small scale maps show fewer details. In the field of geography, the scale is usually divided based on the study area, for example, “town”, “city”, “state”, and “country” (Slocum et al., 2013).

One of the main objectives of this thesis is to understand the effectiveness of 3D and 2D symbols on Virtual Globes under different scales. As the VG is mostly used for visualizing global datasets, the default view for most applications places the VG in the middle of the screen and allows users to see the entire globe. However, when considering the case of Virtual Globe, the traditional 2D map scales do not apply anymore. This is because the Virtual Globes and usual traditional flat maps are originally at different scales and aims to communicate information at different geographic level.

The understanding of scale is always more complicated in 3D environments than in 2D flat maps. There are only a few papers suggesting the division of 3D map scales. Bandrova and Bonchev (2013) conducted a user study with professional users to explore requirements for 3D map scales. Their result indicates that the division of scale for 3D maps depends on the visualization, zooming, and level of details. But in general, professional users think that:

1> Large scale 3D maps: need data sources at scale 1:1000 and larger.

2> Middle-scale 3D maps need sources at scale 1:10 000 to 1:25 000.

3> Small-scale 3D maps need sources at scale 1:50 000 or smaller.

Although VG and 3D terrain/city maps are both in the 3D virtual environment, however, they are different. There are no studies that provide standard guidelines for the division of scales when using a Virtual Globe. For example, a web map with a full computer screen showing geographic information of the European region could be considered as a small-scale map (scale around 1: 250000). However, when applying this scale to the Virtual Globe, the curvature of the earth is completely invisible, and the area being shown is only a “smaller area” contains “more details” compare to the entire globe.

In a desktop environment, usually, the screen is limited in size rather than infinite. When users interact with VG, the limited screen will block the view of the Virtual Globes to a certain extent. For example, when users zoom in on a certain scale, users could see part of the curvature of the VG at four corners of the screen rather than the entire curvature; or when users zoom in on a very large scale, usually to view specific cities or countries with a smaller area, the VG will look like a flat map on the screen because the screen size is way too small to show the entire globe at this scale. The hypothesis is that 3D and 2D symbols have different effectiveness under different scales.

Therefore, in the case of Virtual Globes, the viewing distance should be used instead of the map scale. Considering the Cesium platform provides a developer camera setting, in this thesis, the term camera height is used to substitute the term scale. Each camera height corresponds to a visual situation of the virtual globe. A more specific setting will be introduced in the implementation section.

Three camera heights with slight fluctuate up and down are defined corresponding to the map scales:

1> Large-scale maps: low camera height where the entire globe is visible.

2> Medium-scale maps: medium camera height where only part of the curvature of the globes is visible.

3> Small-scale maps: high camera height where the curvature is invisible, and the VG looks like a flat map.

3.2.2. Symbols Design

Proportional symbols are often placed at the location of the points to represent quantitative data, for example, the earthquake magnitudes, the temperature at the weather station, and the location of the oilfield (Kunigami et al., 2011). Two forms of point data could be represented with proportional symbols (Slocum et al., 2013). The first form is true point data, which refers the the data measured at the exact location. The second form is Conceptual point data. Conceptual point data refers to data that are collected over areas but conceived as being located at points for research or other purpose (Slocum et al., 2013). One example is the dataset used in this study. The population is collected from the entire area of the city, but are represented with specific point location for symbolization. The commonly used symbols are opaque disks or squares (Cabello et al., 2006).

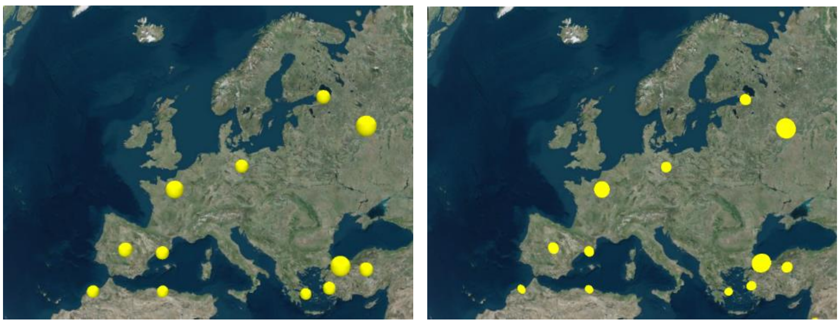
Proportional symbols can be represented by various shapes. In general, there are two classifications of proportional symbols, geometric and pictographic symbols (Ingram, 2020). Pictographic symbols refer to symbols that mirror the phenomenon being mapped (Slocum et al., 2013), for example, use scaled tacos to represent the popularity of taco restaurants. In opposite, the geometric symbols could be circles, squares, cubes, or spheres. This thesis studies the geometric symbols. Although the developed technologies provide the user an easy way to scale their own designed symbol, but the regular shape of pictorial symbols will cause difficulties for users to perceive the size difference.

The design of 3D and 2D symbols considers the following aspects: 1> the shape of the symbols; 2> the direction of the symbols.

The initial shape design consideration is to use a proportional sphere for 3D symbols, and a proportional circle for 2D symbols (Figure 3.2). The placement of the sphere is that the bottom tangent to the virtual globe. The volume of the sphere represents the population of the city to be compared. However, this design is abandoned because of the similarity between 3D and 2D symbols. One of the advantages of Cesium over D3.JS is that it provides well-designed 3D symbols with shadows. But at a certain scale, the 3D and 2D symbols do not look significantly different. Semi-sphere was also in consideration. But this idea is abandoned because of the rendering problem of Cesium at the earth corner. Sometimes it shows the half sphere inside the earth, while the other sites do not.

Bleisch (2011) proved that the 3D bar has a good performance regarding effectiveness in a 3D environment. Another advantage of the 3D cylinder is that users only need to consider the height when comparing the data on VG. This is easier than a sphere because the sphere requires users to consider one more visual variable – depth cue. The difference in effectiveness between value-proportional and length-proportional symbols is also one of the sub-objectives of the study. Therefore, the cylinder is selected for the final representation of 3D symbols. The reason to choose circles for 2D representation is that circle is always more stable (Slocum et al., 2013).

Figure 3.2
Initial design – the shape



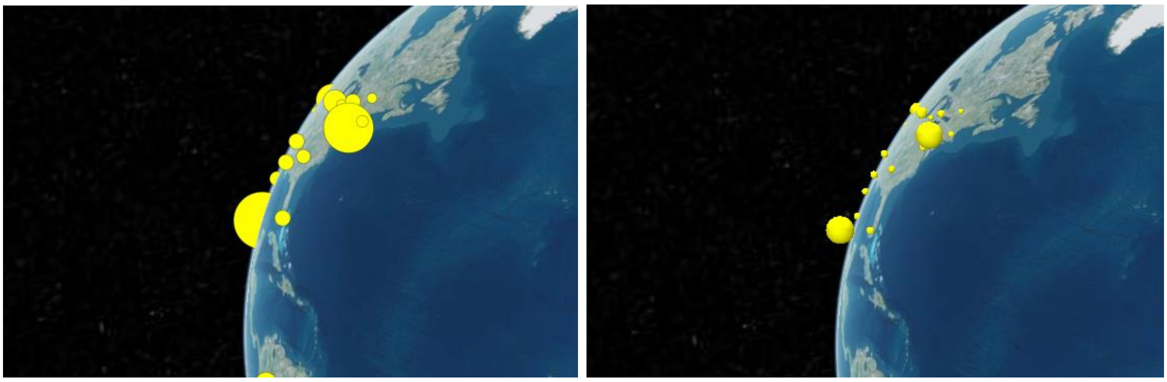
Note. Left: 3D sphere. Right: 2D circle.

The second design problem is the direction of the 3D and 2D symbols. The direction for symbols on virtual globes could be divided into three classifications: Billboard, Normal, and Tangential. Satriadi and other scholars (2021) designed five idioms to test the effectiveness and efficiency of the symbol direction. In their design, the only direction design for the 3D cylinder is the normal direction. The normal direction refers to the three-dimensional bars being aligned with the normal of the sphere's surface. They claimed that this design of direction is the most common representation of quantitative values on a globe based on examples from existing media. Therefore, the 3D cylinders are also placed in the normal direction on VG in this study.

The direction of 2D symbols is trickier than the 3D symbols (Figure 3.3). This study uses proportional circles for 2D symbol representations. Satriadi and other scholars (2021) suggested that the billboard circle is the most efficient idiom, while the tangential circle performs the worst in effectiveness. In their studies, many users claimed that tangential circle is very hard to read, especially at the edge. As the circles are stuck on the surface of the globe, they are all affected by the distortion. At the same time, the users also claim that billboard fits better in the aesthetic aspect. However, the problem of billboard design aligns on the edge of the globe. When zooming in to the edge, some of the 2D circles, where the cities are on the screen, are completely visible. Some of the 2D circles, where the represented cities are not on the screen, are only partially visible. It is noticeable that the half circle has a high similarity to the half sphere. When the city is very close to the edge, the 2D circle will "stand up" at the edge. In this case, the 2D circle has high similarity to the 3D sphere, only without shadow (Figure 3.3, right).

To prevent the confusion bring by the similarity between 3D and 2D symbols, the 2D circles are placed as tangential on the virtual globes.

Figure 3.3
Initial design – the direction



Note. Left: 2D billboard circle. Right: 3D normal sphere.

3.2.3. Proportional Symbol Design

One common problem in using proportional symbols is how the quantitative value is represented by the shape. This always confuses the public users and even researchers who study cartography and related majors.

The mature standards of proportional symbols provided by former researchers already give a clear guideline. In his book "Thematic Cartography and Geovisualization", Slocum and other researchers stated the basic math for symbols.

" For 2D circles:

$$\frac{\pi r_i^2}{\pi r_L^2} = \frac{v_i}{v_L}$$

Where r_i = radius of the circles to be drawn;

r_L = the radius of the largest city;

v_i = data value to be drawn;

v_L = data value of the largest city "

This specified that the circle areas should be in direct proportion to corresponding data values.

After the cancel the constant and taking the squre roots of both sides, the equation reduced to :

$$r_i = \frac{v_i^{0.5}}{v_L^{0.5}} \times r_L$$

Similarly, for calculating 3D cylinder:

$$V = \pi r^2 \mathrm{h}$$

In this study, the area of bottom and top of cylinders are set to constant. By apply the same process, the fomular could be reduced to :

$$h_i = \frac{v_i}{v_L} \times h_L$$

Where h_i = height of cylinder to be drawn;

h_L = the height of the largest city;

v_i = data value to be drawn;

v_L = data value of the largest city

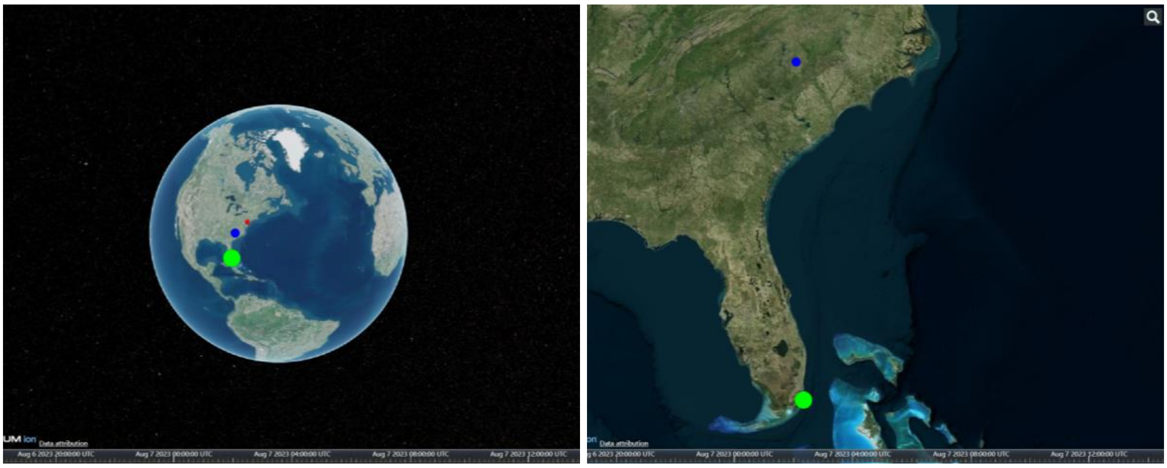
In this prototype, the design of proportional symbols are stick to the existing guidelines. In three-deimension situation, the height of the cylinder are in proportional to the population. To simplify and improve the efficiency, the bottom and top sides of the cylinder are coded to have the same radius. In two-dimension situation, the size of the 2D circle are proportional to the population.

3.2.4. Scale-based Symbol Sizing

The final design problem is the scaled-based symbol sizing. It is common in some web-based applications that the size of the symbols can be adjusted dynamically across their visible scale range. The purpose of this design is to reduce the visual density at a smaller scale and maintain a suitable relative size at a larger scale (ArcGIS Pro).

Figure 18 shows an example of scaled-based symbol sizing in Cesium. The point symbol provided by the platform has a default scaled sizing. The size of the geometry symbols could be scaled by multiplying with a factor in the equation. However, this design also brings a problem in that the relative size between two specific symbols will be changing. The left figure (Fig. 3.4) shows the symbols at a smaller scale, and the right figure shows the symbols at a larger scale. It is visible that the green and blue symbol has a larger size difference at a small scale than larger scale. Considering this problem, the 3D cylinders and 2D circles are designed to have only one size across all the zoom levels. This is to ensure the users will have the same relative size between the two cities even if they slightly zoom in or zoom out.

Figure 3.4
The uniform scale of symbols in Cesium



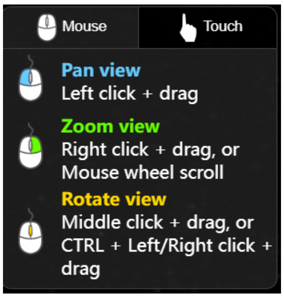
Note. Left: factor scaled symbols at high camera height. Right: factor scaled symbols at low camera height. The 2D circles are coded to multiple scales at different zoom level.

3.3. PROTOTYPE IMPLEMENT

As CesiumJS requires the local server to host, free open-source Apache Tomcat is used. CesiumJS utilizes WebGL and provides developers a Virtual Globe with several types of rendered terrain, popularly used including ArcGIS World Imagery and OpenStreetMap. The default terrain being used is the Bing Map Aerial Image. To provide a clean interface for user study, the timestamps, licenses, clock, and other logos are coded to be turned off. The Cesium platform provides an easy way for users to interact with the prototype (Figure 3.5). Users could simply use the three keys on the mouse to drag and rotate the Virtual Globe.

Figure 3.5

Interact with Cesium prototype



The final design of the Virtual Globe prototype is shown in Figure 3.6 and Figure 3.7. The Virtual Globe is placed in the middle of the screen. The background is set to a black night sky because a pure and high-contrast background could avoid any interference. The button on the left provides the function to switch between 3D cylinders and 2D circles. The button beside provides the function to select tasks. Each task number is followed with "2D" or "3D" to indicate the symbol that should be used for the task. When the user click on the symbol, a green pane will pop up in the middle of the selected city. At the same time, a label showing the name of the city will roll out at the upper-right corner.

Figure 3.6

Final 3D cylinder symbols design

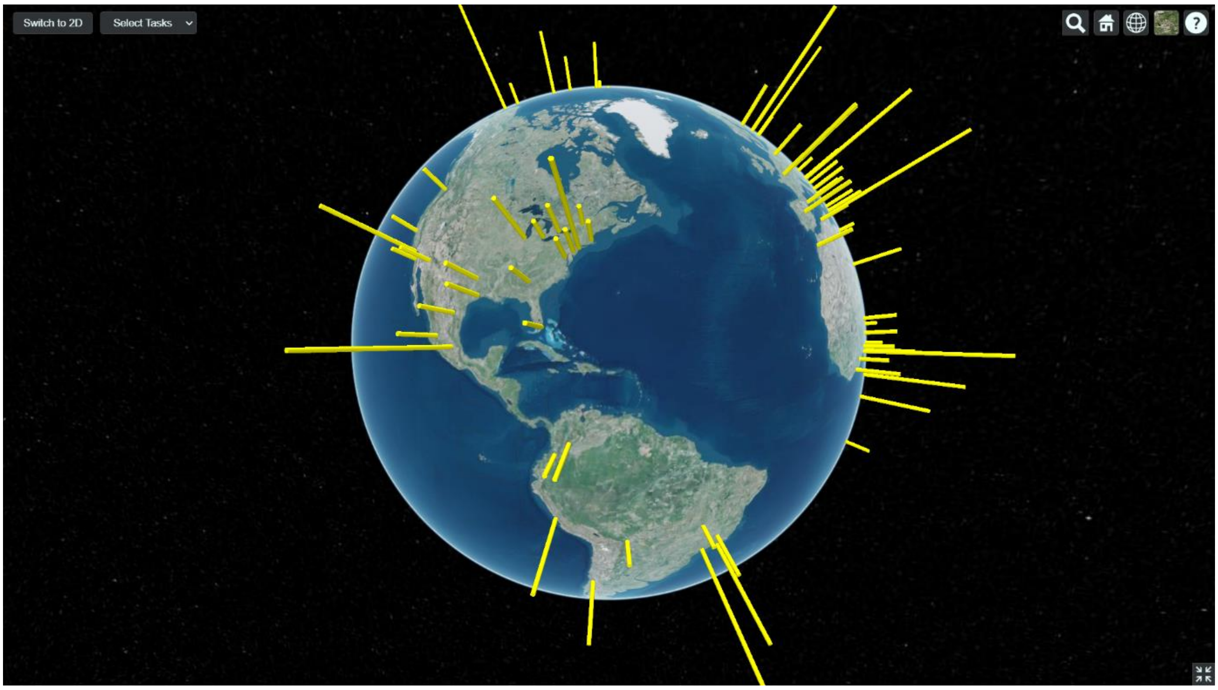
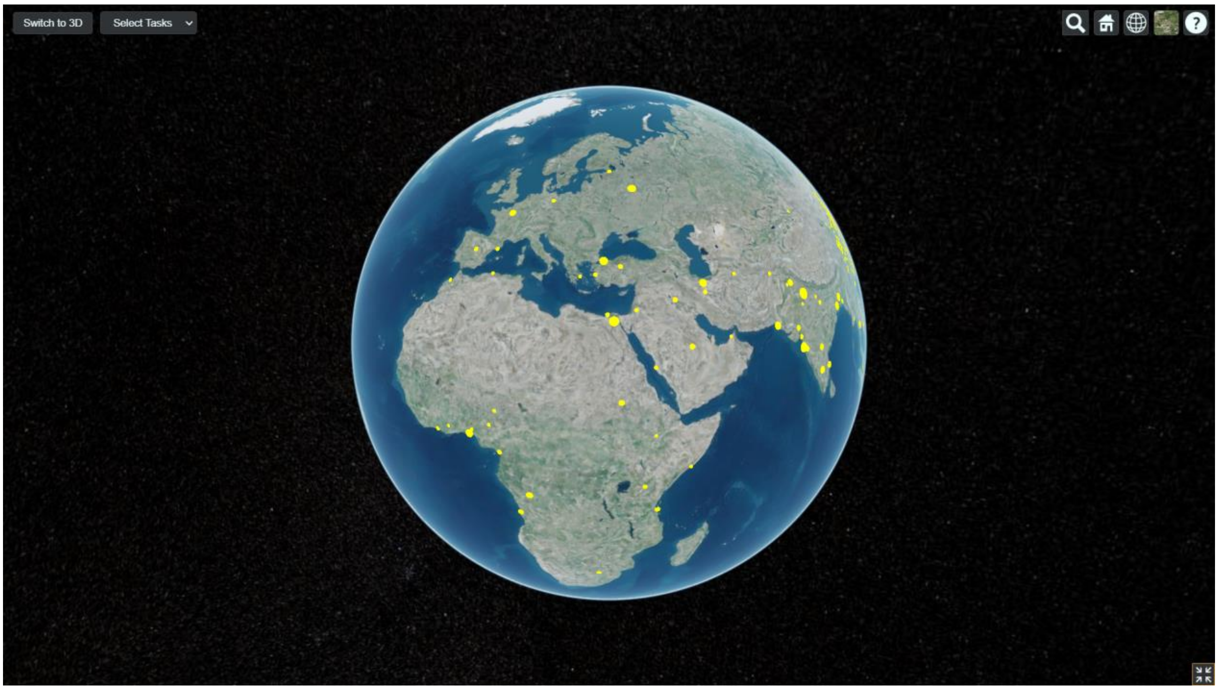


Figure 3.7
Final 2D circle symbols design

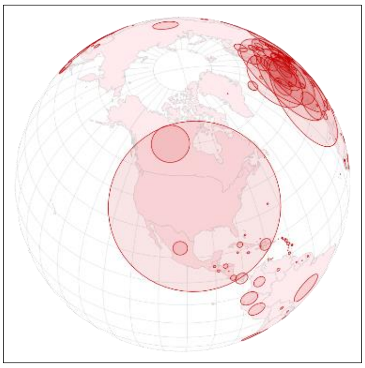


3.4. USER STUDY

After the release of Google Earth, Virtual Globes have been widely used to represent geo-spatial data, especially in the field of cartography, remote sensing, geo-information, and geography. Scholars build Web-based VG applications to explain their research outcome. However, many of the applications are not only faced to cartography experts, but also the public groups who have no experience with VG at all. One example is shown in Figure 3.8 (The Guardian).

Figure 3.8

Example of Virtual Globes application



Note. COVID-19 cases until 8th April, 2020. From "How coronavirus spread across the globe – visualised", by The Guardian.

3.4.1. User Group

One of the main objectives of this study is to investigate how readers with different backgrounds perceive the symbols on the VG. To achieve this goal, the users are divided into two different groups: 1> users with a cartography or graphic design background; and 2> users without any cartography or graphic design background. The target users are university students at the Master's and Bachelor's levels, the division of user group is not strictly based on the study background. Whether they have experience in Cesium or other Virtual Globes platforms is also in consideration.

3.4.2. Prepareation

A question form is prepared for users to answer and fill in the task questions. The users are asked to sign the consent form and fill in the study background information at the beginning of the study. The question form is produced by Qualtrics. The advantage of this questionnaire website is reflected in the possibility of the free version. It allows the developer to collect around one thousand responses for each survey without any limitation in the survey opening period. The result data could be downloaded in various file formats.

The user study is designed to be done in-person or online. For the in-person study, users are provided with the prototype on the developer's laptop. At the same time, users open the question form using their phone or laptop. The prototype is also hosted by a local Raspberry Pi and published online. Online users are provided with the link to the prototype and questionnaire. The instruction is provided for online users. To ensure the quality of the study, an online meeting is hosted at the same time to answer user's questions the as soon as possible.

3.4.3. Tasks and Questions

There are 14 task-related questions in the user study. Including four questions for the small and large scale Virtual Globe, and six questions for medium scale VG.

In order to investigate the effectiveness of the 3D and 2D symbols, users are asked to complete graphic tasks. The tasks include following type:

1> Identify Extreme Value

2> Relative Size (Ratio) Comparison

The relative size comparison is one of the key tasks in the graphic study (Roth, 2013). In this study, the ratio comparison refers to tasks that compare the relative size (identify the ratio) of two cities. This type of task could describe how well the users determine the similarities and differences between two features on a map (Roth, 2013). For comparing the objects on different sides of the Virtual Globes, two questions are set only at small scales. This is because interactivity is one of the most significant characteristics of Virtual Globes. In real applications, when users compare objects on different sides, most users would zoom out until the entire globe is visible.

3.4.4. Camera Height

The Cesium camera is defined by a position, orientation, and view frustum (Cesium). To implement the tasks for user study and provide convenient for users, the camera is designed to "fly" to specific coordinates for each task. An example is shown in Listing 2. The first-two number is the coordinate to place the camera, and the third number is the camera height.

Listing 2

```
function Task1small() {
  viewer.camera.flyTo({
    destination: Cesium.Cartesian3.fromDegrees(40.362707, 57.736663, 25000000.0),
  });
}
```

As explained in the former section, the camera height is used in corresponding to the "map scale" in this study. The default length unit used by Cesium is in meters. As the tasks for user study are limited, it is not possible to test every meter of height. Tasks for the same height level are designed with slightly different heights:

1> Large-scale maps: at 1,000,000; 2,000,000; 2,200,000; 2,500,000 meters.

2> Medium-scale maps: at 7,000,000; 8,000,000; 9,000,000; 13,000,000 meters.

3> Small-scale maps: at 20,000,000; 22,000,000; 25,000,000 meters.

Consider the real-world situation, there are always overlapping of the symbols in the region of East Asia. As the study focuses on the scale and user group, the questions are designed to avoid the regions with much overlap.

As the camera height is one of the study variables, users are allowed to slightly zoom in and out in all directions when interacting with the prototype, but the three levels of views should always be kept. For example, when doing the medium scale tasks, users can zoom in and out, part of the curvature should always be visible. Users are also allowed to rotate the globe as much as they need.

3.4.5. Post-Study Questionnaire

The actual accurate rates and the subjective feeling of users might be different. Users might have high preference in one type of symbols while the symbols have low effectiveness. A post-study questionnaire is added at the end of the study to investigate user's subjective feelings. There are in total seven questions including following aspects:

1> Comparing 2D and 3D symbols, the mental loads at different camera height when completing the tasks.

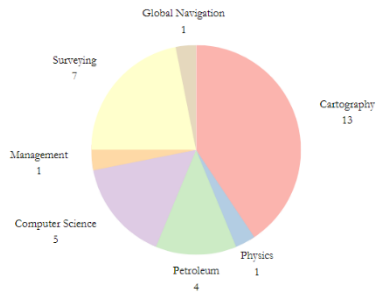
2> Comparing 2D and 3D symbols, the preference for symbols at different camera height.

3> User's subjective feelings for 3D and 2D symbols at different situation (when comparing cities on different sides of the globe; when comparing cities next to each other)

4. RESULT

The User study was conducted from the 24th of July until the 20th of August. In total, 32 participants provided completed responses. The cartography group included fourteen participants studying Cartography at the Technical University of Munich, and three participants studying Surveying Engineering and Global Navigating Systems at Wuhan University, who both have experience in using Cesium Virtual Globe to visualize Lidar Data in recent research. The non-cartography group included four users studying Petroleum Engineering, five users studying Computer Science, five users studying surveying engineering without any experience in Virtual Globes, one user majoring in Physics, and one major in Management (Figure 4.1).

Figure 4.1
Study major of participants

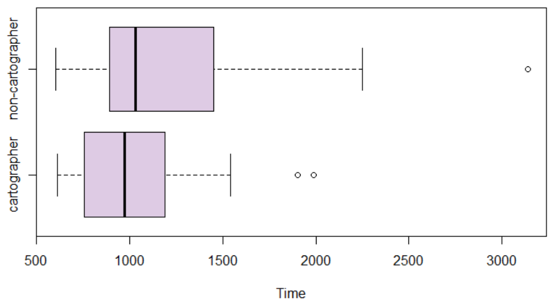


4.1. EFFICIENCY

The efficiency data is first tested with the Shapiro-Wilk function to check the normal distribution, which is a method that fits small samples (Mishra et al., 2019).

Efficiency is not the main measurement of this study. The questionnaire does not provide a function to record the time for each answer while some of the users completed the study online. However, the users were asked to finish the questions as soon as possible. Shapiro-Wilk test indicates that both group data are not normally distributed ($p < 0.05$). One efficiency is removed from the calculation as it is an extreme value that does not make sense for the study. The average time for all users to complete the study is 1185.61625 seconds. The average time of the cartographer group is 1065.56 seconds ($W = 0.86184$, p-value = 0.02045). The average time of the non-cartographer group is 1305.67 seconds ($W = 0.79318$, p-value = 0.002214) (Figure 4.2). The box plot of non-cartographers shows the right-skewered trend.

Figure 4.2
Box plot of efficiency

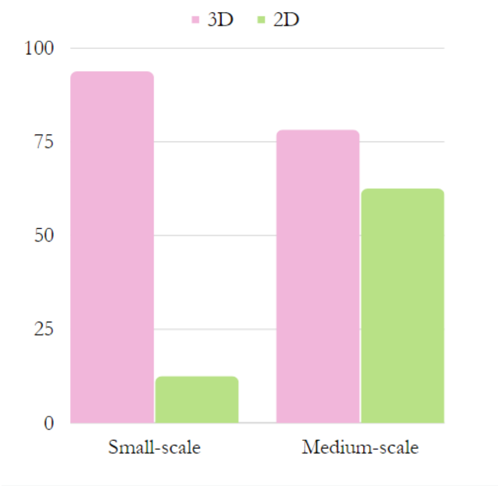


4.2. EFFECTIVENESS

For “identify extreme value” tasks, there are two questions at small scales and two questions at medium scales. When using the 3D cylinders at small scale, the correct rate of the cartographer group is 87.5%, while the non-cartographer group is 100%. When using 2D circles at small scale, the correct rate of both groups is 12.5%. When using 3D cylinders at medium scale, the correct rate of the cartographer group is 81.25%, while the non-cartographer group is 75%. When using 2D circles at the medium scale, the correct rate is 56.25%, while the non-cartographer group is 68.75% (Figure 4.3).

Figure 4.3

Identify extreme value tasks overall correct rate



Shapiro-Wilk test is applied to check the distribution of response for relative size comparison tasks. The result indicates that all the series of response does not follow normal distribution. In size comparison tasks, sometimes the users might have answers that are far from the given options. Considering this situation, these questions were provided as open answers, where users could fill the ratio that best fits their senses. To conduct statistical analysis for the response, the Wilcoxon test (Childs et al., 2021) at a significant level of 0.05 is applied to compare the difference between each response to the correct answer (Table 4.4). A significant medium difference ($p < 0.01$) is detected at the large scale when using 3D cylinders. Small differences are detected at small scale and medium scale when using 3D cylinders, but not significant ($p > 0.1$, $p > 0.1$). For 2D circles, significant medium difference between users’ responses to the correct answer is detected at small scale ($p < 0.01$), medium scale ($p=0.01$), and large scale ($p<0.01$).

Table 4.1

Compare all users’ response with correct answer

Symbols	Scale	Group All		
		Z	p	r
3D	small scale	0.8	p = .446	0.1
	medium scale	0.9	p = .386	0.1
	large scale	-2.8	**p = .006**	-0.3
2D	small scale	2.8	**p = .005**	0.5
	medium scale	-2.6	p = .010	-0.3
	large scale	-3.9	**p < .001**	-0.5

Table 4.2 shows the comparison of different user groups' responses to the correct answer.

Within the cartographer group, only no significant very small difference is detected when using the 3D cylinders. Significant large difference is detected when using 2D circles at small scale ($p < 0.05$) and large scale ($p < 0.01$), significant medium difference is detected at medium scale ($p < 0.05$). Within the non-cartographer group, no significant difference is detected at small scale and medium scale when using both 3D cylinders and 2D circles. A significant large difference appears when using the 3D symbols at the large scale ($p < 0.05$), while a significant medium difference is detected at the large scale when using 2D circles.

Table 4.2

Compare user group response with correct answer

Symbols	Scale	Group Cartographer		
		Z	P	r
3D	small scale	-0.3	p = .736	-0.08
	medium scale	-0.009	p = .993	-0.002
	large scale	-1.5	p = .137	-0.3
2D	small scale	2.1	**p = .039**	0.5
	medium scale	-2.1	**p = .032**	-0.4
	large scale	-2.8	**p = .004**	-0.5
Symbols	Scale	Group Non-Cartographer		
		Z	P	r
3D	small scale	1.5	p = .123	0.4
	medium scale	1.4	p = .152	0.3
	large scale	-2.5	**p = .010**	-0.5
2D	small scale	1.9	p = .058	0.5
	medium scale	-1.5	p = .136	-0.3
	large scale	-2.5	**p = .013**	-0.4

Note. Significance is detected at $p = 0.05$ level.

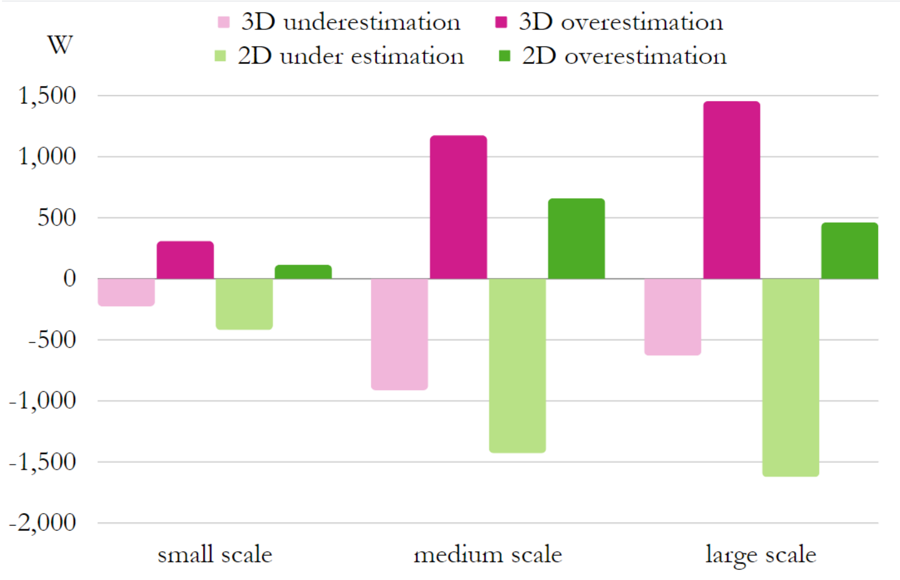
Overestimation and underestimation of symbol ratio is also a common problem in the graphic study. Figure 4.4 shows the W+ and W- calculated by the Wilcoxon test. W- is calculated from where the user response is larger than the correct answer (Under-estimation of ratio), and W+ is calculated from observations where the user response is smaller than the correct answer (Over-estimation of ratio).

The comparison shows that when using 3D cylinders for relative size comparison, users are more likely to overestimate the ratio between two objects on Virtual Globes. At small scales, the difference between overestimation and underestimation is not significant. As the zoom level becomes larger, the likelihood of overestimation also becomes larger and more significant. When using 2D circles, users are more likely to underestimate the relative size between two objects on Virtual Globes. As the zoom level becomes larger, the probability likelihood of underestimation also becomes larger and more significant.

The comparison is also conducted for different user groups. For the cartographer group, the likelihood of underestimation and overestimation is similar when using 3D cylinders at small scales and medium scales. At large scale, there is a higher likelihood that users overestimate the ratio between objects (W- = 184, W+ = 344). When using 2D circles, a large likelihood difference appeared at all scales (small scale: W- = 108, W+ = 28; medium scale: W- = 379. W+ = 149; large scale: W- = -416, W+ = 112). Users are more likely to underestimate the ratio between objects. For the non-cartographer group, the same trend of underestimation is found at three scales when using 2D circles. Besides, the likelihood of overestimation of ratio when using 3D cylinders is found at three scales. The likelihood becomes larger as the zoom level becomes larger.

Figure 4.4

W+ and W- of all user



4.3. OPEN QUESTIONS

For the optional open question "Why do you prefer 3D / 2D symbols?", participants stated the answers from different aspects.

Three cartographers stated that it is hard to decide, the preference depends. One user explained: "First of all, the application of geographical symbols should depend on the objects carried by geographical symbols and the geographical scene used. Personally, I prefer 2d symbols, because 2d symbols conform to the traditional electronic map form. And compared with 3D symbols, the layer overlay visual effect of 2D symbols feels clearer. 3D symbols have certain information redundancy in the expression of dense map symbols."

Two users from two groups stated that they prefer 2D symbols because: "Cesium does not work very smooth when interacting with the globe using 3D cylinders", and: "With the prototype running very slowly, 2D gives a much more comfortable look and feel". Five users from two groups stated that they prefer 2D symbols because it is easier for comparison. One user stated that: "2D symbols are preferable because the 3D symbols may extend off-screen when viewed from some angles".

Three users stated that at large scale and medium scale, 3D symbols are preferable. One user explained: "On the entire globe/curvature I prefer 3D, it's easier to spot differences because the spots dot disappears with the curve."

4.4. SUBJECTIVE FEELINGS MEASUREMENT

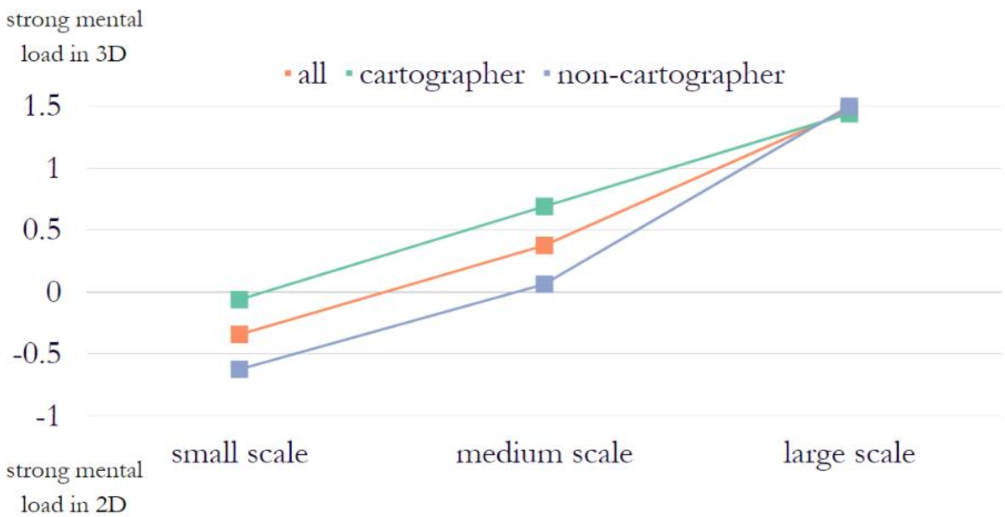
Shapiro-Wilk test were firstly applied to check the normality of subjective ratings. This step is necessary because when the data follow the normal distribution, the analysis method would have a more accurate result, and different method should be applied when the data follows different distribution (Cleophas & Zwinderman, 2016). Referencing the method used in Satriadi et al. (2019), Kruskal-Wallis H Test and Post-hoc Dunn's test with a Bonferroni correction (Cleophas & Zwinderman, 2016) is selected to compare the difference between groups of rating.

4.4.1. Mental Load and Preference

Users were asked to rate their mental load when completing the tasks comparing 2D circles to 3D cylinders (-2 representing strong mental load using 2D symbols over 3D symbols, 2 representing strong mental load when using 3D symbols, 0 represent no difference). The Shapiro-Wilk test indicates that the result does not follow normal distribution. The overall rating at small scale ($W = .84, p < .001$) is -0.344, at medium scale ($W = .88, p = .002$) is 0.375, at large scale ($W = .61, p < .001$) is 1.469 (Figure 4.5).

Figure 4.5

Mental load rating mean value



The Kruskal-Wallis H test indicated that there is a significant difference in the overall rating of mental load across different scales (χ^2 (2) = 33.06, $p < .001$). The post hoc test states that the difference appears between small scale – large scale and medium scale – large scale.

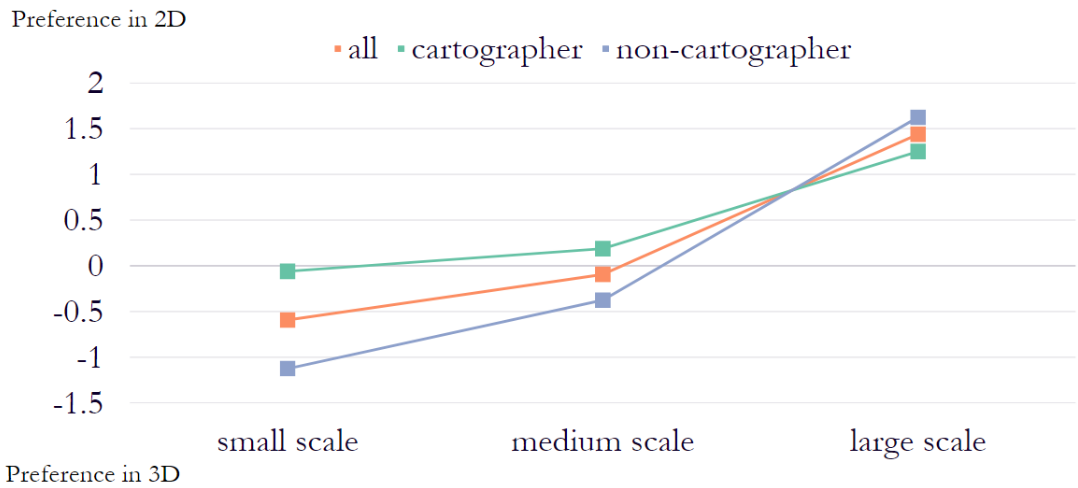
The difference in rating mental load is checked within the group and across the group. A significant difference is detected within the cartographer group (χ^2 (2) = 13.67, $p = .001$) at small scale – large scale. For non-cartographer users (χ^2 (2) = 18.9, $p < .001$), a significant difference is detected between small scale – large scale and medium scale – large scale. No significant difference in rating is detected between cartographer group and non-cartographer group at small scale ($F = 1.340, p = 0.2562$), medium scale ($F = 3.0864, p = 0.08915$), and large scale ($F = 0.03132, p = 0.8607$).

Users were asked to rate their preference comparing 2D circles to 3D cylinders. In order to make a comparison with mental load, the rating is processed with -1 (-2 representing preferred 3D symbols over 2D symbols, 2 representing preferred 2D symbols over 3D, 0 representing no difference)(Figure 4.6). The overall rating mean value at small scale ($W = .83, p < .001$) is -0.593, at medium scale ($W = .91, p = .011$) is -0.094, at large scale ($W = .68, p < .001$) is 1.438. A significant difference in preference rating is detected across scales (χ^2 (2) = 34.45, $p < .001$). The difference appears between small scale – large scale and medium scale – large scale.

The same different pairs are detected within cartographer group (χ^2 (2) = 9.71, p = .008) and non-cartographer group (χ^2 (2) = 24.12, p < .001). No significant difference is detected across user groups at medium and large scale, it is detected at small scale (F=5.1424, p = 0.03071).

Figure 4.6

Preference rating mean value



4.4.2. Objects on the Different Sides of the Virtual Globe

Users were asked to rate how they felt about the effectiveness of 3D cylinders and 2D circles when the two objects are not on the same sides of the globe (where 1 represents poor performance, 5 represents high performance). The overall rating for 3D cylinders (W (32) = .89, p = .003) is 2.688, while for 2D circles (W (32) = .89, p = .004) is 2.656. ANOVA (Cleophas & Zwinderman, 2016) test at the significance level p < 0.05 was applied to check the difference between groups (Table 4.1). No significant difference is detected between different pairs.

Table 4.3

Rating for symbols representing objects on different sides of Virtual Globes

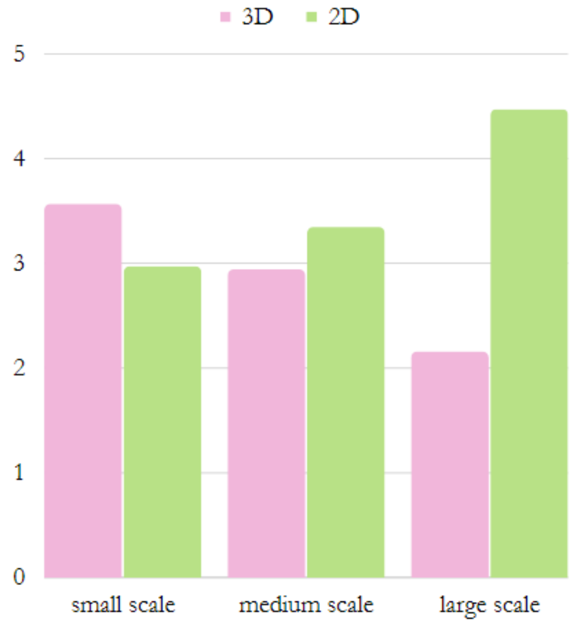
	Mean		S		F	p (<0.05)
Group (Pair x -y)	x	y	x	y		
All (3D - 2D)	2.688	2.656	1.176	1.181	0.011	0.916
carto (3D-2D)	2.375	2.875	1.204	1.088	1.519	0.227
non-carto (3D-2D)	3.000	2.438	1.095	1.263	1.811	0.189
3D (carto-non_carto)	2.375	3.000	1.204	1.095	2.359	0.135
2D (carto-non_carto)	2.875	2.438	1.088	1.263	1.102	0.302

4.4.3. Objects next to Each Other

Users were asked to rate how they felt about the effectiveness of 3D cylinders and 2D circles when the two objects to be compared were next to each other on the globe (where 1 represents poor performance, 5 represents high performance) (Figure 4.7). The result of the Shapiro-Wilk test indicates that the rating does not follow the normal distribution. The overall rating for 3D cylinders at small scale ($W(32) = .87$, $p = .001$) is 3.563, at medium scale ($W(32) = .91$, $p = .012$) is 2.938, at large scale ($W(32) = .78$, $p < .001$) is 2.063. The overall rating for 2D circles at small scale ($W(32) = .88$, $p = .002$) is 2.969, at medium scale ($W(32) = .9$, $p = .007$) is 3.344, at large scale ($W(32) = .56$, $p < .001$) is 4.469.

Figure 4.7

Average rating in performance when objects are next to each other



Across scales. When selecting 3D cylinders, the Kruskal-Wallis H test indicated that there is a significant difference between the different viewing scales ($\chi^2(2) = 18.48$, $p < .001$), with a mean rank score of 62.48 for small scale, 49.72 for medium scale, 33.3 for large scale. When selecting 2D circles, a significant difference between different viewing scales is also detected ($\chi^2(2) = 26.1$, $p < .001$).

A significant difference in rating is detected within the cartographer group for 3D cylinders ($\chi^2(2) = 6.72$, $p = .035$) at small scale and large scale. For 2D circles, a significant difference is also detected within the cartographer group ($\chi^2(2) = 11.55$, $p = .003$) at small scale and large scale.

For the non-cartographer group, a significant difference in rating when using 3D cylinders ($\chi^2(2) = 11.76$, $p = .003$) is detected between both small scale – large scale and medium scale – large scale; a significant difference is detected for 2D circles ($\chi^2(2) = 16.02$, $p < .001$) between small scale – large scale and medium scale – large scale.

Across symbols. Difference in rating is checked across symbols (Table 4.4). A significant difference is detected within the cartographer group at both medium scale and large scale. The result also indicates that the non-cartographer group has significantly different ratings at large scale. Overall, there is a significant difference at large scale. Other pairs do not have significant differences.

Table 4.4
Performance of symbols when objects are next to each other across symbols

		small scale	medium scale	large scale
carto	F	2.1302	3.8235	17.8525
	P (0.05)	0.1548	**0.0599**	**0.0002**
non_carto	F	1.5092	0.0000	41.5404
	P (0.05)	0.2288	1.0000	**0.0000**
all	F	3.6112	2.1802	55.1514
	P (0.06)	0.0621	0.1449	**0.0000**

Across user groups. Difference in rating is also checked across groups (Table 4.5). The result indicates that there is a difference when using 3D symbols at medium scale. No other significant difference is detected.

Table 4.5
Performance of symbols when objects are next to each other across user groups

		small scale	medium scale	large scale
3D	F	0.4494	5.7874	0.3943
	P (0.05)	0.5077	**0.0225**	0.5348
2D	F	1.2565	0.0252	0.2364
	P (0.05)	0.2712	0.8749	0.6303

5. DISCUSSION

5.1. EFFICIENCY

Cartographers are more confident when completing the graphic study on Virtual Globes. From Figure 4.2 it can be seen that despite few extreme values, the cartographer group on average spends less time than the non-cartographer group. The medium value of non-cartographers is slightly higher than cartographers. The result could indicate that cartographers need less time to think about the tasks.

In usual cases, cartographers are the ones who create Virtual Globes applications that face the public. Therefore, the result regarding the time for completing the study is not surprising considering that cartographers are more familiar with the graphic design guidelines than public users.

5.2. EFFECTIVENESS

Summarizing the result of this study, the following conclusion could be drawn:

Effectiveness for all users:

1> Statistically, the effectiveness of 3D cylinders performs well at small and medium scale. It becomes worse as zoom in.

When objects are located close to each other, users need to rotate the globe to specific angles to see the contrast between two one-dimensional objects. At small scale and medium scale, as the view is larger, the degree of rotation where users need to see the contrast is lighter. At the large scale, users need a stronger degree of rotation to view the contrast.

2> The effectiveness of 2D circles does not perform well at all scales of zoom level, especially at small scale and large scale.

At the small scale, the distortion of 2D symbols is the main problem affecting the effectiveness. As one of the users mentioned in the open question, the 2D circles disappear with curvature and rotation. The distortion affects users' judgment of the size, especially when the objects are close to the edge of the Virtual Globe on the screen.

At large scale, the dimension is the main problem affecting the effectiveness. The question: "Whether the area of the circle represent the population or does the radius of the circle represent the population" was frequently asked by users from both groups during the study. As zoom in and focus on two specific objects, there might be no other objects surrounding to provide a reference. Users are more likely to be disorientated when measuring and comparing two dimensions in this case.

3> Users are more likely to overestimate the 3D cylinders, underestimate the 2D circles. The likelihood of overestimation and underestimation becomes larger as the zoom level becomes larger.

The overestimation of 3D cylinders has been rarely mentioned in previous empirical studies for 2D maps and Virtual Globes. The assumption for the overestimation is caused by the adaptation level mentioned by Cox (1976) in the precious symbols study. Cox (1976) stated that the estimation of the size of the symbols is based on a referencing middle point. Therefore, readers are likely to overestimate the large symbols and underestimate the small symbols. Considering the large length of cylinders in the normal direction, the overestimation might be explained.

Many scholars have indicated that the size difference represented by circles is usually underestimated by readers on traditional 2D maps (Flannery, 1971). The result in 2D circles on Virtual Globes fits the theory from previous research and guidelines.

4> When objects are not on the same side of the globe, users have no preference in 3D and 2D symbols, but 3D cylinders statistically perform better.

In this case, users always must memorize the length or shape of the first object. It could be seen that the impact of visibility and the requirement of memorization is much larger than the design of the symbols itself. Only a slight difference could be seen across user groups that cartographer users prefer 2D circles while non-cartographer users prefer 3D cylinders. This might be because when memorizing the symbols, one-dimension symbols are easier for users who do not have graphic study experience.

5> 3D cylinders are more effective in representing similar values than 2D circles at small scale and medium scale.

In early research, Merhoffer (1973) stated that map readers have difficulties in distinguishing small variations in the circle size. The result of this study fits this theory. The difference might be caused by the dimension of the symbols. The difference in size is more obvious in one-dimension changes rather than two divided into two dimensions.

Across user groups:

1> The effectiveness of 3D cylinders performs well for cartographer users at all zoom scales, and performs bad for the non-cartographer users at large scale.

2> The effectiveness of 2D circles perform bad for cartographer user at all scales, perform bad for non-cartographer user at large scale.

3> Cartographer users have strong perceptions to underestimate 2D circles at all zoom scales. The non-cartographer users have strong perception to overestimate 3D cylinders and underestimate 2D circles only at large scale.

The reason of bad performance of both 3D and 2D symbols at large scale is explained in previous section. Losing the referencing middle point when zoom in the Virtual Globes, non-cartographers are more likely to have mis-perception without knowledge or experience in graphic and VGs. The result of bad perception of 2D circles at all scales by cartographers is surprising. The assumption is that cartographers are confused by the knowledge of the graphic guidelines. While knowing that map readers are more likely to underestimate the circle size, cartographers might take more consideration rather than use the first impression of difference directly. During this response time, the mental measurement then led cartographers to have an even more underestimated answer.

From users' perspectives:

1> 3D cylinders are preferred at the small scale, 2D circles are preferred at the large scale. The preference is strong for the non-cartographer users over the cartographer users.

2> The non-cartographer users have stronger mental load when using 2D circles at small scale and medium scale, both groups have strong mental load when using 3D symbols at large scale.

As expected from the effectiveness, the 3D cylinders are preferred at small scale. Although the 2D symbols have worse performance, and users tent to have stronger mental load when using 2D circles it is preferred by both user groups at large scales. The "flat" symbols fits better when the Virtual Globes zoom in looks like a "flat" map.

One point is that in the actual value represented by symbols is given in most of the real applications. Users do not need to identify or compare the value "blindly" only from the size of the symbols. In these cases, the aesthetic aspect of design should be considered as same as the effectiveness of symbols. Besides, the perceptions of public users should also be considered for better communicating the information.

Medium scale:

Medium scale could be a more complicated case. This is because there is no standard division of scale for Virtual Globes. The medium scale is defined according to the visibility of the Virtual Globe in this study. It can not be considered as an exact point where the dynamic design should happen.

From the result, 3D cylinders have better effectiveness than 2D circles for both user groups. The likelihood of overestimation/underestimation is also smaller when using 3D cylinders rather than 2D circles. However, the subjective feelings measurements indicate that users have a stronger mental load when using 3D cylinders at the medium scale than 2D circles. Cartographer users have a slight preference for 2D symbols and non-cartographers have a slight preference for 3D symbols.

Therefore, as mentioned by some of the cartographer users, at this scale range, the visualization and design of symbols should always consider the density of the objects, the purpose of the visualization, the target readers, and other influencing factors.

5.3. LIMITATIONS

Several limitations are acknowledged in this study for evaluating the effectiveness of 3D and 2D symbols under different situations and by different groups. The limitations could mainly be classified as 1> limitations from theory; 2> limitations from user study; 3> limitations from technology.

5.3.1. Limitations From Theory

In this study, the user tasks with the highest appeared frequency are the relative size comparison tasks. Although it is recognized as one of the key tasks, it involves small number of geometry entities, and the tasks themselves are at an "easy" level (Andrienko & Andrienko, 2005). As there are no previous studies focused on the scale for virtual globe and different user groups, this study aims to provide a basic understanding of these two variables. With more complex tasks, the result might again differ from the current conclusion.

As the scale for virtual globes is dynamic, it is impossible to include every scale section in the user study. For medium scale, the user study can only provide suggestions rather than certain guidelines for all the applications. The design of symbols should always reference the data type and the purpose of visualization apart from the result of this study. With further research, the medium camera height situation might also have better and more clear recognition.

Due to the limitation of time and financial situation, the study only used a small sample for each group and scale. In future studies, a large sample should be tested for more accurate conclusion.

5.3.2. Limitations From User Study

In total there were 32 users participated in this user study. Half of the users did the study in-person and half of the users did the study online. During the study, all the other environmental variables are controlled. In-person users were given the laptop with the prototype, and online users were asked to open the prototype on the laptop. Users were asked to zoom as little as possible and to stick with the three defined camera heights. However, users might "destroy" the designed tasks to a certain degree which is not controllable. For example, in some tasks, especially medium camera height and low camera height, the user might flip the globe to compare the 3D cylinders, which makes the boundaries between the two camera heights become blurred.

The users were filled into cartographer group and non-cartographer group based on their study background and experience with virtual globes. However, as most of the participants are students at the Master's and Bachelor's level, the experience of users in their study major does not exceed 10 years. The question: "Whether the radius represents quantitative variable or the circle area represent quantitative variable" appeared in both groups of users. The experience of cartography users is limited. Because of the access to expert users, the samples may not provide the best effect in explaining the difference between two groups.

Another element that are not controllable is the response quality caused by user's personal reasons. All participants are appreciated. Most of the users participated in the study without having any rewards. However, the response quality is related to the user's mood and patience when completing the tasks. This could be influenced by the extreme environment and the things they are going through.

5.3.3. Limitations From Technology

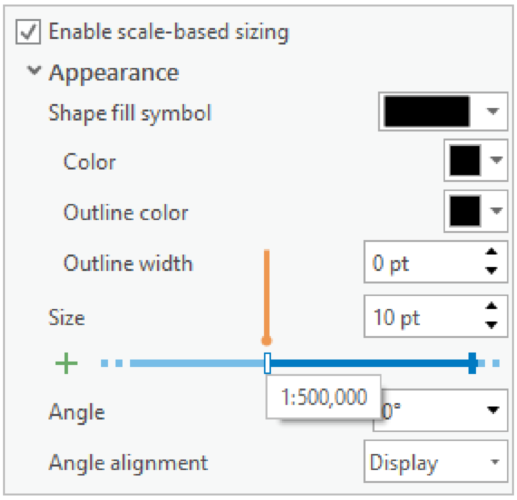
Although the current technology has obtained huge progress in past decades, it is still not able to fulfill all the research ideas. Cesium is a powerful platform for visualizing earth geo-data. After Google Earth stopped the plug-in service in 2016 (Munasingh et al., 2017), Cesium has become one of the most frequently used 3D virtual globe platforms. However, Cesium suffers from JavaScript limitations and performance issues (Mete et al., 2018). Different browsers might implement different JavaScript engines, and the performance of Cesium thus would be varied. Besides, Cesium provides the user with an easy way to interact with the globe. However, in the question: "Why do you prefer 3D/2D symbols?" one of the cartographer users stated: "Cesium does not work very smoothly when interacting with the globe using 3D cylinders". As the investigation of preference is included in the post-study, the smoothness of the platform is influencing the result.

The Efficiency of the 3D and 2D symbols is not the main measurement for this study, even though the questionnaire records the start time and close time of the question form. For in-person users, a prototype with original files supported by a local host is provided to interact personally. For online users, the prototype is hosted by local Raspberry Pi. The data pipeline of Cesium has numerous requirements. Therefore, a powerful back-end server is usually necessary for CesiumJS applications (Buck et al., 2021). In the optional open answer, one user stated that: "the prototype is running slower when using 3D cylinders". As some of the users are in Asia, the remote connections might have slight delays. The situation depends on the user's internet connection and other influencing elements.

Another limitation is the scaled sizing. The "point" entity is designed with default scaled sizing. However, this scaling by distance does not work properly for geometry, for example, the 3D cylinder and 2D circles used in this study. As Cesium scales the geometry with respect to the Cartesian system origin, it might shift the position of the geometry. One of the reasons might be that apart from the visualizing of global data, there are more developers who utilize Cesium for city models, where the scaled sizing is not necessary. For future development, it would be helpful if the Cesium platform had settings to scale the geometry. One referencing example is the setting slices in ArcGIS Pro (Figure 5.1).

Figure 5.1

Scale sizing in ArcGIS Pro



Note. From Create Points from a Table, by ArcGIS Pro Document

6. CONCLUSION

This chapter summarized the idea, method, and result of this study; Proposed several possible research directions for future cartographers.

6.1. SUMMARY

Despite the popularity of Virtual Globes as geospatial data visualization applications, little empirical study has been conducted on the effectiveness of Virtual Globes and the use of symbols. In the early stage, the research direction is limited to comparing 2D maps and Virtual Globes. After the release of Google Earth, researchers started to compare the effectiveness of these two visualizations, and explore the function of Virtual Globes for thematic mapping and choropleth visualization. A few years ago, researchers compared the effectiveness of 2D symbols on 2D maps and Virtual Globes. Only in recent years, scholars started to examine the utilization of both 3D and 2D symbols with different visual variables.

The development of technology brought a diverse virtual environment. The creation of Virtual Globes is not limited to desktop environments anymore, but also to Virtual Reality, Augmented Reality, and Mixed Reality. However, the study of the effectiveness of Virtual Globes in these immersive environments is still at an infantile stage.

The overarching research objective for this study is to understand and explore the effectiveness of 3D and 2D symbols on Virtual Globes under different circumstances based on the existing symbolization guidelines. The influencing variables include 1> the different viewing scales of Virtual Globes and 2> the perception by different user groups.

A literature review has been conducted to understand the development of Virtual Globes and the related empirical study. The evaluation of symbols' effectiveness is done by conducting a user study with 32 participants. The participants are filled into the cartography group and non-cartography group. A Web-based prototype with 3D cylinders and 2D circles is developed by using JavaScript as a tool for visualization. CesiumJS is selected as the platform for the prototype. The prototype is hosted with a local server so the users can access from both in-person and online.

The result of this study indicates that at small scale, the 3D cylinders are more effective than the 2D circles, and the effectiveness of 3D cylinders becomes worse as the zoom level becomes larger; 2D circles perform badly at all zoom scales, but are preferred by both cartographer and non-cartographer users at large scale for a more pleasant aesthetic design. Both user groups are more likely to overestimate the 3D cylinders and underestimate the 2D circles. The likelihood of overestimation and underestimation becomes larger as the zoom level becomes larger. Users' preference and effectiveness of 2D and 3D symbols do not show significant deviation at medium scale. Overall, the cartographer users are more confident when completing the tasks.

Rather than indicate a specific point where the symbols on Virtual Globes should change from 3D to 2D, this study uses the result of the user study to propose the idea that dynamic symbols changing with zoom level could be a better design for Web-based VG applications. However, the specific changing point should always consider the purpose of visualization, the targeting users, the density of the objects, and other influencing factors.

The outcome of this research could be useful in helping the future development of Virtual Globes applications. In real applications, the value represented by the symbols is usually given to the users, therefore the effectiveness, efficiency, and aesthetic aspects should be taken into account in the design. The dynamic symbols changing with the zooming level could be considered for better information communication and a more pleasant user experience.

6.2. FUTURE DIRECTION

Cartographers still need further research to explore how the virtual globes could be utilized more effectively and efficiently. Figure 6.1 summarizes the previous developing stages of virtual globes and symbols, addresses the current study, and proposes potential research direction in the future.

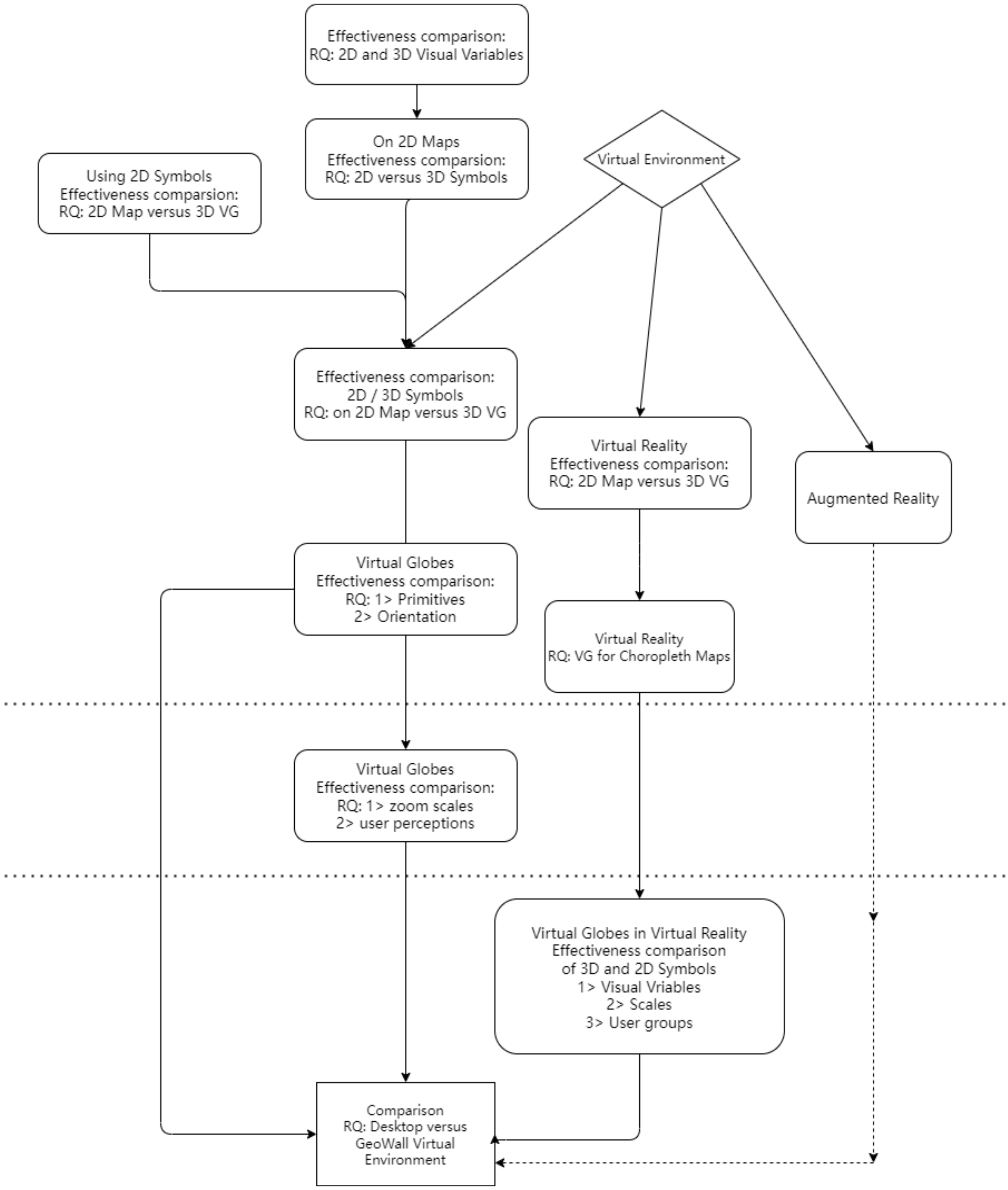
6.2.1. Visual Variables

Apart from the size, shape, and orientation, the hue is also one of the most effective visual variables for both 2D and 3D symbols (Liu et al., 2017). However, the existing research uses symbols with uniform colors to support the empirical study of other variables. There is no research bringing the study of color to the symbols on virtual globes so far.

As explained in the previous section, the existing research and current study only use the basic graphic tasks to provide a rough understanding on variables such as 1> primitives; 2> placing directions; 3> scales; 4> user groups. User studies with more complex tasks should be conducted in order to figure out more clear and comprehensive design guidelines. As Satriadi and other researchers (2021) proposed, the potential complex tasks could be pattern identification, and relation-seeking, which might suggest different results than the current conclusion.

Figure 6.1

Empirical research regarding on virtual globes and symbols



Note. RQ: Research Questions.

6.2.2. Virtual Reality

An attempt was made to implement a prototype in the Virtual Reality environment at the beginning of this study. The idea was to build a prototype as same as the desktop environment, and conduct a user study to explore how users perceive symbols at different scales in different virtual environments. However, due to the limitations in time and technology, the attempt failed.

Some potential research questions are proposed here for future study:

1> How to build a virtual globe to represent quantitative data in Virtual Reality? What platform could be used?

Building prototypes in Virtual Reality could be more complex than in a desktop environment as more advanced equipment is involved. Cesium provides two platforms that make it possible to create a VG prototype: plug-in for Unity and Unreal.

Cesium Unity was released in November 2022 (Cesium), it provides developers with a full-scale high-accuracy WGS84 globe. However, many functions are still limited. The plug-in works for Universal Render Pipeline (URP) and High Definition Render Pipeline (HDRP) (Cesium). However, the built-in renderer is not supported. The render of datasets loaded by Cesium will not show properly if developers use empty 3D templates.

Cesium for Unreal was released in March 2021. Kloiber and other researchers (2022) utilized this plug-in to explore the virtual globes for choropleth maps. With further research, VR VG for quantitative visualization will appear in the view of the public.

2> How to conduct a user study in a Virtual Reality environment?

In comparison to the user study for the desktop environment, the VR environment makes the practical experiment more difficult. As users need HMD to see the immersive screen, it is not possible to have users take the HMD off and on to type the answer in the online questionnaire. In this case, two solutions might be possible. One way is to conduct an oral user study, another way is to implement the question and answer inside the prototype.

3> How do 3D and 2D symbols work compared to desktop environments and Virtual Reality environments?

In previous literature, Slocum and other scholars (2013) stated then users are more likely to be disorientated in a Virtual Reality environment. The VR provides users with infinite screen and interact with the globe. Immersive technologies are the trend of development. It is worth exploring whether the design guidelines of symbols on VGs should be different as well.

6.2.3. EFFICIENCY

The measurement of efficiency could be more difficult than effectiveness. Most of the online questionnaire tools only record the start time and end time for the entire survey. The time for answering each question is not recorded. In this case, the usual method to measure the efficiency would be to record manually with a stopwatch. The method also brings measure errors. For example, users might have different time in reading the questions or interacting with the prototype. In a VR environment, the proposed two methods to conduct user study could lead to even larger measure errors. In the future study, optimized methods are needed for measuring the efficiency of symbols on VGs.

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APPENDIX 1

User study tasks and questionnaire:

BG

Please share your background/study major.

Page Break

Q1 3D

Identify the city with the largest population (cities in screen)

Page Break

Q2 2D

Identify the city with the largest population in America continent.

Q3 3D

Identify the approximate ratio of population - Ibadan : Lagos

Page Break

Q4 2D

Identify the approximate ratio of population - Moscow : Delhi

Page Break

Q5 2D

Identify the approximate ratio of population - San Diego : Los Angeles

Q6 3D

Identify the approximate ratio of population - İzmir : Athens

Page Break

Q7 2D

Identify the approximate ratio of population - Jakarta (Indonesia) : Rio de Janeiro (Brazil)

Page Break

Q8 3D

Identify the approximate ratio of poopulation - Berlin (Germany) : Tokyo (Japan)

Q9 2D

Identify the approximate ratio of population - Montréal (Canada) : Mexico city (Mexico)

Page Break

Q10 3D

Identify the approximate ratio of population - Madrid (Spain) : Barcelona (Spain)

Page Break

Q11 2D

Identify the approximate ratio of population - Seoul (South Korea) : Busan (South Korea)

Q12 3D

Identify the city with the lowest population in Africa

Page Break

Q13 3D

Identify the approximate ratio of population - Seattle : Miami

Q14 2D

Identify the city with highest population in Africa

Page Break

Q15

Please compare your mental load when doing the task with 2D and 3D symbols.
-2 represent: have strong mental load when using 2D. (feels 2D more difficult to do tasks)
0 represent: does not have significant mental load difference when using 2D and 3D symbols
2 represent: feels 3D is harder to do the task

	-2	-1	0	1	2
When you see the entire globe					
When you see part of the curvature					
When zoom in you see a "flat map"					

Q16

Please compare your preference when doing the task with 2D and 3D symbols.
-2 represent: have strong preference in 2D symbol.
0 represent: does not have significant preference between 2D and 3D symbols
2 represent: have strong preference in 3D symbols.

	-2	-1	0	1	2
When you see entire globe					
When you see part of the curvature of the globe					
When zoom in you see a "flat map"					

Q17

Why do you prefer 3D / 2D symbols? (optional)

Q18

How is 3D cylinder symbols working when two objects are not on the same side of the globe (can not see both at same time in static screen)
5 represent good performace.
1 represent poor performance.

1	2	3	4	5

Q19

How is 2D circle symbols performing when two objects are not on the same side of the globe (can not see both at same time in static screen)
5 represent good performace.
1 represent poor performance.

1	2	3	4	5

Q20

How is 3D symbols perform when two objects are next to each other
5 represent good performance
1 represent poor performance

	1	2	3	4	5
when you see entire globe					
When you see part of the curvature of globe					
when you see a "flat" map					

Q21

How is 2D symbols performing when two objects are next to each other.
5 represent good performance
1 represent poor performance.

	1	2	3	4	5
When you see entire globe					
When you see part of curvature of the globe					
When you see a "flat" map					

APPENDIX 2

Code to build prototype:

https://github.com/Cartograqi/VGJavascript

Access to Prototype:

http://map.sonnenberg.app

Users Study Response:

https://github.com/Cartograqi/VGJavascript