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Combining Quantitative Eye-Tracking and GIS Techniques With Qualitative Research Methods to Evaluate the Effectiveness of 2D and Static, 3D Karst Visualizations: Seeing Through the Complexities of Karst Environments

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COMBINING QUANTITATIVE EYE-TRACKING AND GIS TECHNIQUES WITH QUALITATIVE RESEARCH METHODS TO EVALUATE THE EFFECTIVENESS OF 2D AND STATIC, 3D KARST VISUALIZATIONS: SEEING THROUGH THE COMPLEXITIES OF KARST ENVIRONMENTS

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By
Elizabeth Katharyn Tyrie

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COMBINING QUANTITATIVE EYE-TRACKING AND GIS TECHNIQUES WITH QUALITATIVE RESEARCH METHODS TO EVALUATE THE EFFECTIVENESS OF 2D AND STATIC, 3D KARST VISUALIZATIONS: SEEING THROUGH THE COMPLEXITIES OF KARST ENVIRONMENTS

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Karst environments are interconnected landscapes vulnerable to degradation. Many instances of anthropogenic karst disturbance are unintentional, and occur because of the public's lack of understanding or exposure to karst knowledge. When attempts are made to educate the general public about these landscapes, the concepts taught are often too abstract to be fully understood. Thus, karst educational pursuits must use only the most efficient and effective learning materials. A technique useful for assessing educational effectiveness of learning materials is eye-tracking, which allows scientists to quantitatively measure an individual's points of interest and eye movements when viewing a 2D or 3D visualization. Visualization developers use eye-tracking data to create graphics that hold the observer's attention and, thereby, enhance learning about a particular concept. This study aimed to assess and improve the educational effectiveness of 2D karst visualizations by combining eye-tracking techniques with Geographic Information Systems, knowledge assessments, and semi-structured interviews. The first phase of this study consisted of groups of 10 participants viewing 2D karst visualizations with one category of manipulated visual stimuli. The second phase consisted of groups of 10-15 participants viewing 2D karst visualizations that were created based on the results from the first phase. The results of this study highlighted both effective stimuli in karst visualizations and stimuli that hinder the educational effectiveness of visualizations.

CHAPTER ONE: INTRODUCTION

Karst environments are characterized as landscapes underlain with carbonate rocks that have distinctive surface and subsurface features such as springs, sinkholes, caves, and aquifers. These environments are significant, interconnected landscapes that are vulnerable to contamination and degradation through anthropogenic action (Veni et al. 2001), yet supply 20-25% of the world's population with drinking water (Ford and Williams 2009). Examples of anthropogenic impacts to karst landscapes include groundwater degradation, cave destruction, and biota habitat loss. Many of these impacts are unintentional and occur largely because of the public's lack of understanding and exposure to karst knowledge. When attempts are made to educate the general public about these landscapes, the concepts taught are often too abstract or complicated to be accurately understood (North 2011). For example, the surface/subsurface connectivity of karst features is an important, yet difficult, scientific concept for individuals to understand since these features exist primarily below the land surface and are not easily visible. The difficulty in visualizing and understanding this distinct characteristic of karst is exaggerated when these concepts are taught to non-science and/or non-geoscience minded members of the general public, and even further exacerbated when ineffective or inaccurate educational karst diagrams, photographs, and/or infographics are used in educational pursuits.

Adding to the current, largely ineffective status of public karst education is regulatory limitation and monetary and time constraints of land managers to oversee the protection of karst environments (Fleury 2009). Thus, since regulatory protection is largely unavailable or ineffective, in order to minimize occurrences of anthropogenic karst disturbance, the learning outcomes of educational pursuits must be maximized through the development of efficient and effective learning materials. An important step in ensuring the production of such learning materials can be to assess the educational effectiveness of cave and karst visualizations distributed to the public through geocognition research aided by eye-tracking.

Eye-tracking is a technique used to quantitatively measure an individual’s points of interest and eye movements when viewing a 2D or 3D visualization. By tracking these movements with specialized devices, a scientist is able to correlate eye movements to the attention path demonstrated by an observer (Duchowski 2007). Through the correlation of eye movement to attention path, researchers are able to identify the regions of interests (ROI) in the image, fixations (how long the observer views ROI), and in what order ROI are observed. By calculating the image’s specific ROI, researchers have the ability to understand processes that support cognitive development and behavioral activities (Duchowski 2007). For example, visualization developers are able to use eye-tracking techniques to create scientific graphics that hold the observer’s attention and enhance cognition about a particular educational topic through the manipulation of visual stimuli since visual stimuli can elicit attention by the observer to particular ROIs (Jacob and Karn 2003; Mayer 2010; Coyan 2011). Commonly manipulated visual stimuli include label placement and content, visualization orientation, topic-specific land features, scale notation, and color. Through the scientific graphic development process aided by eye-tracking, researchers are able to disregard visualizations that distract or disinterest the observer and instead focus on visualizations that direct understanding while exposing observers to complex concepts that are difficult to comprehend.

This study sought to address the gap in existing geocognition literature related to visualizing karst landscapes and perpetuating karst knowledge by combining eye-tracking technology with quantitative Geographic Information Systems (GIS) techniques and qualitative research methods to investigate how people interpret karst diagrams. This study sought to develop new educational diagrams that effectively and efficiently communicate karst and groundwater concepts to non-karst experts. Specifically, through the use of stationary eye-tracking technology, this research addressed the following three research questions:

1) What framework and methodology are needed to investigate the effectiveness of karst visualizations using a mixed-methods approach with quantitative eye-tracking technology, GIS statistical analysis, and qualitative methods?
2) What are the characteristics of an effective karst instructional visualization, and how do these characteristics impact understanding of karst environments?
3) What are the similarities and differences between 2D and static, 3D karst visualizations in terms of the observers' learning about karst environments?

From these questions the research objectives for this study were:

1) to develop a framework for best practices when using a triangulated, mixed-methods approach to study learning outcomes of karst visualizations,
2) to determine, through eye-tracking, the differences and trends in attention processes based on karst geology expertise when viewing karst visualizations,
3) to establish the visual stimuli characteristics in karst educational visualizations that are most effective at educating about complex karst landscape characteristics,

4) to identify the similarities and differences in observers' learning when viewing 2D and static, 3D karst visualizations, and
5) to establish if static, 3D visualizations are more effective at improving an observers' understanding of karst environments.

The objectives were achieved in this study with the use of eye-tracking, knowledge assessment, and semi-structured interviews. This type of methodology represents one of the most innovative and promising means by which to improve karst educational visualization materials. Eye-tracking allows researchers to reveal statistically significant trends in the way observers' perceive and fixate on visualizations in an effort to expose the cues influencing observers' understanding of the illustrated concept. In this study, the use of eye-tracking technology, in conjunction with outcomes assessments and interviews, allowed for data collection from many participants to answer each of the aforementioned research questions, achieve their associated research objectives, and perpetuate the development of educationally effective karst visualizations for the public.

Public education through visualizations, when used effectively, is a powerful tool to motivate society to improve conservation and management efforts. This type of motivation is particularly important for karst regions where education and management strategies are generally lacking due to ineffective educational materials and decreased budgets. As anthropogenic impacts on karst environments are ever increasing, karst educational materials from this study are needed to improve public understanding of the detrimental impacts humans have on their drinking water and livelihood.

CHAPTER TWO: LITERATURE REVIEW

Twenty to twenty-five percent of the world's population depends on the water resources afforded by fragile karst environments for survival (Ford and Williams 2007), yet these resources are currently under threat of severe degradation from anthropogenic action. To reduce these negative anthropogenic impacts, efforts must be made to educate the general public about the significance of karst environments and the impacts of human interactions with these systems. Karst interpretive displays are commonly used to educate the public about karst environments and the role humans play in karst longevity. However, the effectiveness of these displays in communicating relevant information about karst is understudied. This research combined eye-tracking techniques, GIS statistical analysis, and qualitative methods to investigate how people interpret karst educational materials, specifically the karst diagrams, for the purpose of developing new visualizations that more effectively and efficiently communicate karst and groundwater concepts to non-karst experts. Thus, a complete understanding of the interconnectedness of karst landscapes and investigation of eye-tracking capabilities is imperative. A comprehensive examination of environmental education, formal and informal learning, and scientific visualizations is also necessary to gain an understanding of how non-karst experts learn from educational displays and interpretative signs. Lastly, GIS techniques that can benefit the analysis and visualization of eye-tracking data is reviewed.

2.1 Karst Environments

A karst environment is defined as a landscape that has a surface underlain with carbonate rocks and distinctive surface and subsurface features that develop through the dissolution of the carbonate bedrock (White 1988; Ford and Williams 2007; Palmer 2007). Karst regions comprise 12% of the world's ice-free land surface and are found on every continent except Antarctica (Veni et al. 2001). Perhaps the most important natural resource of karst landscapes is freshwater, since these terrains supply 20 to 25% of the world's population with drinking water (Ford and Williams 2007). In addition to water resources, karst environments also support entire underground ecological systems and have a variety of other resources of paleontological, archeological, and geological importance. Yet, even with all of the valuable resources available from karst areas, fragile karst landscapes are experiencing increased anthropogenic threats that are severely impacting these non-renewable environments (Veni et al. 2001).

2.1.1 Evolution of Karst

The formation of a karst landscape is an ongoing process, taking place over several centuries, with five elements in consideration: rock type (the geological element), solvent (the climatic element), fracture (the structural element), gradient (the topographic element), and time (the historic element) (Groves 1993). Karst landscapes are generally formed in carbonate rocks that are distinctive due to their sedimentary nature and susceptibility to post-depositional alteration (Ford and Williams 2007). Limestone represents the most predominant karst bedrock due to its high solubility and secondary, or fracture, porosity (Ford and Williams 2007). The second karst landscape forming element, solvent, requires an environment that supports high levels of $C0_2$ from the atmosphere and/or decaying vegetation and an abundance of water, usually in the form of rainfall (Groves 1993). When rainfall or streams come into contact with $C0_2$ in the atmosphere and soil, the water and

$C0_2$ molecules bind together to form carbonic acid. Then, as the acidic water seeps into the soil and interacts with carbonate bedrock, a $CaCO_3$-CO_2-H_2O chemical reaction is catalyzed, breaking the calcium carbonate compound into HCO^{3-} and Ca^{2+} ions and initiating the dissolution process (White 1988).

In order for dissolution to occur throughout the epikarst (where acidic water and rock meet), water must be able to travel throughout the bedrock via fractures (Groves 1993). Fractures in carbonate bedrock occur most commonly along joints, bedding plains, and faults. Yet, even with the existence of fractures, high porosity and permeability are not the only factors that allow water to travel through carbonate rock. Hydrologic relief, or the fourth element, gradient, is also necessary to move water through the rock and promote the karstification process (Groves 1993; Palmer 2007).

This dissolution process ultimately creates a highly interconnected system of unique karst landforms and complex hydrology. Karst interconnectedness and the landscape's display of unique surface and subsurface features makes it particularly difficult for the public to visualize karst environments in their entirety. This results in a lack of karst understanding by the public, which can lead to increased occurrences of degradation of karst features such as caves and groundwater.

2.1.2 Threats to Karst

From the description of karst evolution, it is apparent that karst formation is highly dependent on five specific elements and largely motivated by the presence of water. Therefore, human-induced environmental change is reflected most by impacts to the hydrologic process (Ford and Williams 2007). Any form of pollution that enters a karst environment can impact the entire system. The most common forms of pollution associated with negative anthropogenic impacts stem from fertilizer, pesticide, herbicide, and septic tank runoff, accidental chemical spills or intentional dumping, landfill leakage, the filling of sinkholes with organic or inorganic material, drainage wells, deforestation, desertification, and mining (Veni et al. 2001; Ford and Williams 2007; North et al. 2009).

These karst environmental threats, especially in the form of contaminants, have severe impacts on groundwater contamination in karst aquifers (Veni et al. 2001). The karst carbonate geology, morphology, and hydrogeology (rapid flow of water through fractures, joint, and conduits), make karst landscapes particularly vulnerable to the concentrated movement of contaminants towards groundwater supplies (Parise and Pascali 2003). Specifically, when contaminated substances flow into streams on the surface and/or direct subsurface inputs, such as sinkholes, they can carry the polluted water resources long distances through networks of conduits, joints, and fractures carved into the karst landscape. The public must be informed or be made aware of how their actions can result in negative impacts on karst environments, especially as freshwater resources continue to diminish. Some political states are at the brink of war over freshwater resources. Even in countries where freshwater is not scarce, groundwater contamination can have severe public health risks for the surrounding communities who rely on a karst aquifer. For instance, in 2000, seven people died and 2,000 people became ill from, a contaminated karst aquifer in Ontario, Canada, that had an outbreak of pathogenic bacteria (Palmer 2007).

Besides the contamination threat to karst areas, these landscapes also are susceptible to landscape destruction and hydrological process disturbance. Many rural areas have drilled wells into karst aquifers to retrieve groundwater for drinking purposes because they have no access to a municipal water supply. Wells, along with quarrying and mining, can depress the water table and lead to sinkhole development and cave collapses (Ford and Williams 2007). Moreover, filling sinkholes and caves with foreign matter can lead to many karst drainage problems such as sinkhole flooding or concentrated water pollution (Veni et al. 2001). Thus, because of the breadth of potential anthropogenic disturbances, the ease with which degradation can occur in karst landscapes, and the need to prevent unintentional disturbance, the necessity for effective karst education and regulation becomes evident.

As karst resources are rapidly depleting and negative environmental impacts on karst landscapes are ever increasing due to human population growth, “regulatory gaps in karst protection still exist due to public apathy for policies and municipality budgetary and time constraints” (North 2011, p. 25). These regulatory gaps could, in part, be due to a lack of understanding of the interconnectedness of karst features by land managers. For example, in a study by Fleury (2009, p. 46), 48% of participants connected to municipality departments identified the “most serious karst-related problem” as groundwater contamination, and 63% suggested that cave protection is the “least important karst-related problems,” despite these two concepts being directly related since caves serve as a conduit for pollution to reach groundwater supplies. Van Beynen (2011, p. 351) goes on to suggest that many karst areas have “no municipal codes or ordinances that manage how humans and karst systems interact.” Even if karst regions have karst-specific regulations, many have discrepancies that compromise effectiveness related to zoning and storm management ordinances (van Beynen 2011). Thus, effective karst education is needed to fill these regulatory gaps and other monetary and time constraints of land managers, and elicit a better understanding and appreciation of karst landscapes, if the valuable resources of cave and karst environments are to be sustained.

2.2 Environmental Education

In order to study effective karst environmental education, one must first understand the definition and implication of environmental education. In the late 1960s, Stapp (1969) declared the foundational goals of environmental education are to make citizens more knowledgeable about the biophysical environment and associated problems, determine methods to help solve these problems, and provide motivation towards solutions. Roth (1970) formally defined environmental education as instilling knowledge about biophysical and sociocultural environment and fostering awareness of management alternatives for solving environmental problems. This marked the beginning of the development era for environmental education throughout the 1970s, which included the passing of the National Environmental Education Act by the U.S. Congress, the creation of the Office of Environmental Education in the U.S. federal government, and the release of the foundational Tbilisi Declaration by the United Nations Education and Scientific and Cultural Organization. Almost fifty years later in the present day, Roth's (1970) environmental education definition can be extended to reflect the movement by scientific curriculum developers, like the National Academy of Sciences, to create conceptual frameworks that encourage integration between different scientific disciplines (National Research Council 2012). A revised definition of environmental education in the present-day is an integrative approach to study scientifically-complex environmental problems that cannot be appropriately investigated by a single, scientific discipline (Malandrakis 2006). With this integrative approach, the purpose of environmental education is to increase society’s knowledge and awareness of the environment (NEEAC 1996). By increasing knowledge and awareness, environmental education seeks to change peoples’ attitudes and instill personal motivations for them to alter behavior and take sound environmental actions to solve environmental problems (NEEAC 1996).

While environmental education has continued to evolve since the 1970s, it has recently received attention due to an increased demand for education that focuses on sustainable development at all levels of the U.S. government and internationally (Payne 2006). Even with the increased demand to develop environmental education curriculum, the majority of research in the environmental education research field has focused on youth in the formal learning setting (Gough et al. 2001). Yet, according to North (2011, p. 35), citing an earlier study, “the average person only spends approximately three percent of his or her lifetime in school; merely a small percent of a person’s knowledge is actually obtained in formal educational settings.” Informal learning, an alternative to formal learning that promotes real-world and lifelong learning, has received far less consideration in environmental education research (North 2011).

Formal education is a form of learning that requires a teacher in the position of authority to establish rules and requirements that ensure students acquire knowledge and learn effectively from a pre-established curriculum (Hein 1998; Bekerman et al. 2006). Formal education takes place in schools and institutions by licensed instructors. As opposed to formal education, informal education is a form of learning that occurs when instruction happens in an incidental and spontaneous learning situation without a progressive, established curriculum or guide of an instructor or mentor (Hein 1998; Bekerman et al. 2006). The National Research Council (2009), Griffin (1998), and Falk and Dierking (2000) definitions are combined to describe informal education experiences as, learner-motivated, driven by learner interests, voluntary, personal, ongoing, contextually relevant, collaborative, nonlinear, and open-ended. Rather than licensed instructors, informal teachers can be park tour guides, museum guides, camp counselors, troop leaders, etc. in places such as parks, museums, zoos, science and nature centers, and show caves. Educational opportunities at these venues include tours, workshops, exhibits, interactive displays, interpretive videos, and brochures, amongst others (North 2011).

2.2.1 Informal Learning Research

Since the majority of learning occurs outside of formal school settings, this study largely focused on tools that can be used for informal learning. Because the investigation of karst education in either formal or informal learning environments is largely nonexistent (North 2011), the following review mainly incorporates museum and science center informal learning research contributions. In the 1990s, the detailed study of learning in informal learning environments was just beginning (Anderson et al. 2003). Thus, compared with formal learning research contributions, the study of informal learning in science museums, and especially karst-specific learning environments such as show caves, is still in its infancy (Ramsey-Gassert et al. 1994; Anderson et al. 2003).

According to Boisvert and Slez (1994), there are three prerequisites for learning in museums including attraction by drawing a subject’s attention, holding power by maintaining the subject’s attention, and engagement by soliciting the subject to interact with the exhibit. In their study relating to the interactions of students with two exhibits in a science center, Botelho and Morais (2006) investigated the third prerequisite of Bernstein’s theory of pedagogic discourse by analyzing students’ behavior when interacting with exhibits along with the students’ understanding of scientific concepts presented in the exhibits. The results of their study suggest three characteristics of exhibits have influence on students’ learning: the exhibit’s design, the set of mechanisms connected with the exhibit’s function, and the criteria for evaluation (Botelho and Morais 2006). In other words, the exhibit must be designed have mechanisms and concepts that are clearly presented with objects corresponding to the core concepts and written words or expressions for students to acquire the scientific concepts (Botelho and Morais 2006).

Although the results of the aforementioned study demonstrate proof of learning in an informal setting, they also suggest more detailed studies are needed to explain their findings and that future studies should carefully consider exhibit characteristics specific to the concepts being taught (Botelho and Morais 2006). This study aimed to fill the gaps of informal learning research that were highlighted in Botelho and Morais (2006) by applying the conclusions drawn from their foundational study to the field of karst geoscience and complement it with the use of eye-tracking. Doing so, allowed for the identification of the attention path and fixations of both karst expert and karst non-expert subjects to determine effective and ineffective characteristics in karst and groundwater instructional tools.

Botelho and Morais (2006) note that many factors affect exhibit-student interaction including previous knowledge, the reading of labels, and the design of the exhibit. However, Bamberger and Tal (2007) used data from over 750 students in 29 classes from 4th-8th grade specifically to explore the influences of task behavior, linkage to prior knowledge and school science curriculum, and linkage to students' life experiences on the students' informal learning experiences. Data from the students were gathered from four different museums that offered various levels of choice to the students as they explored the museums. Four types of choice were revealed by the examination of the data including no choice (when guides led the students through the exhibits throughout the entire museum visit), limited choice (when guides allowed students to explore the exhibits on their own while using some type of structured direction), and free choice (when guides allowed the students to freely explore the exhibits independently) (Bamberger and Tal 2007).

Findings from Bamberger and Tal (2007) indicate that, for the most part, no-choice guides did not inquire about prior knowledge or previous life experiences. In addition, some of the no-choice guides presented complex scientific concepts that the students did not understand with such limited interaction. Limited choice did not necessarily adhere to school curriculum, but the students were engaged, had competitions with each other, and excelled when worksheets provided scaffoldings for learning. In the free choice museum activities, students complained of too much time, did not read labels, and were not as engaged as they were in limited choice activities. Thus, the study presents evidence that limited choice informal learning activities allow for more engagement of students in the learning process by providing some structure but allowing students to control their learning. The Bamberger and Tal (2007) results also indicate, in all of the choice opportunities, prior knowledge and experiences play a crucial role in student learning in informal settings. Thus, this study examined participants' prior knowledge and experiences by incorporating relevant questions into the pre and post eye-tracking survey instruments.

While the findings of the Bamberger and Tal (2007) study strongly indicate limited choice learning to be most effective in museums, their data analysis procedures involved analyzing mostly qualitative data collected from observation, semi-structured interviews, and museum worksheets without pre- and post- outcome assessments. By calculating fixations and scan paths of a subject through eye-tracking, a more quantitative approach to informal learning engagement is presented with more statistically significantly results. In addition, in this eye-tracking study, pre- and post- outcome assessments were incorporated to serve as a quantitative measure of learning outcomes from the use of karst visualizations.

Compared to informal research on visitor learning in museums, research on natural park visitor learning is relatively non-existent (North 2011). However, a study by Brody and Tomkiewicz (2002) was conducted in Yellowstone National Park to determine how park visitors' understandings, values, and beliefs are affected by visits to the park. The study's findings most closely follow the Contextual Model of Free-Choice Learning studied by Bamberger and Tal (2007). The researchers revealed, through pre- and post- interviews, that park visitors' learning was influenced through understanding of prior geological concepts, discussions of interpretive signs and their park experiences, and desires to learn because of the uniqueness of the landscape (Brody and Tomkiewicz 2002). Furthermore, the researchers determined additional learning variables that were not included in the free-choice learning model. The most important learning variables influencing attained knowledge of visitors' during the park visit were the visitors' background knowledge regarding a particular subject and visitors' existing beliefs (Brody and Tomkiewicz 2002). In fact, most research conducted on free-choice learning emphasizes the role of prior knowledge in learning (Anderson et al. 2003), and, as such, the survey instrument and accompanying semi-structured interviews used in this project specifically uncovered observers' prior knowledge of karst environments.

While research on informal learning outside of museums is very limited, research on informal learning in karst environmental settings is even more lacking, even though a few attempts to create cave exhibits and displays to communicate the importance of karst and cave environmental resource conservation to the general public have been pursued (Goodbar 1999). Although these projects were intended to educate and spur attitude changes in general public towards the protection of karst environments, there were no follow up studies to determine their educational effectiveness. In order to effectively communicate the importance of karst environments and eliminate karst misconceptions that the general public may have, this study examined key determinants of effective karst interpretive signs and displays through both qualitative and quantitative measures, which are missing from the majority of previous karst, and even broadly in situ geoscience, educational research studies.

2.3 Eye-Tracking

Since its start in the 1970s, eye-tracking has progressed into the mainstream scientific community as a result of the advancement in self-calibration techniques, more accurate and robust fixation identification algorithms, higher efficiency data processing, and greater accessibility of eye-tracking hardware devices (Rayner 1998; Mayer 2010). Eye-tracking is a computational technique that allows researchers to quantitatively identify the eye movements related to points of interest of an observer by detecting his/her scan path when viewing a 2D or 3D visualization. By tracking a person's eye movements, a scientist is able to coordinate those movements to the attention path that is demonstrated by the observer (Duchowski 2007). Attention can be defined in two parts: foveal, what kind of detail is present at the time of fixation, and parafoveal, where the observer looks next (see multiple references in Duchowski 2007). Through eye-tracking techniques, scientists are able to use coordinates estimated through the user's gaze to determine a projected Point of Regard (POR), also known as Point of Interest (POI) (Duchowski 2007). The POI coordinates relating to a user's eye movements are tracked to determine and decipher fixations, meaningful pauses over regions of interest, and saccades, rapid movement occurrences between fixations (Salvucci and Goldberg 2000). By calculating fixations through POI coordinates, it is possible to gain insight into the users visual processing and attention to determine a visual search path.

Calculating a visual search path through eye-tracking techniques can lead to an understanding of specific regions of interests that support cognitive and behavioral activity (Li et al. 2012). Eye-tracking techniques are utilized to study behavior related to image scanning, scene perception, typing, reading comprehension, and language processing (Rayner 1998; Stine-Morrow et al. 2010; Shake and Stine-Morrow 2011). In the 21st century, eye-tracking techniques have evolved to study behavior related to more complex 3D visualizations and animation environments in numerous fields (Bouchieux and Lowe 2010), most notably in education and advertising (Jacob and Karn 2003; Mayer 2019). Recently, using eye-tracking to study student behavior relating to education in the geosciences has resulted in cutting edge research. For instance, Maltese et al. (2013) used mobile eye-tracking to investigate how geology students learn how to conduct fieldwork by observation. Furthermore, in the classroom setting, Rosengrant et al. (2011) used mobile eye-tracking technology to follow student gaze patterns in physical science lectures. The findings of their study, suggested students focused on information presented in PowerPoint slides rather than on the instructor, and the classroom presented many distractors to the students' attentions spans (Rosengrant et al. 2011). Another eye-tracking study related to geoscience education used eye-tracking techniques to understand the use of visual stimuli or cues to highlight key features through color and leader line approaches in geovisualization maps. The study's preliminary results suggested that leader lines are just as effective and efficient as using variable color to link information in coordinated displays (Griffin and Robinson 2010).

2.3.1 Eye-Tracking Contributions to Visualization Learning

With eye-tracking technologies, scientists in educational research fields can define the driving forces and characteristics of effective and ineffective scientific visualizations. Scientific visualization can make science more accessible and allows for the development of images that resemble physical phenomena (Gordin and Pea 1995). Unfortunately, with the potential promises of scientific visualizations comes the reality that in educational settings students are not informed or do not understand how to effectively interpret and use diagrams or other visual aids (Libarkin and Brick 2002). This presents a challenge to educators to use the strength of scientific visualizations to positively influence the students' learning about a particular concept. Visualizations, as opposed to text-only information, in science learning are particularly useful when trying to convey nonlinear or real-world observations and complex systems (Libarkin and Brick 2002; Lewalter 2003). In particular, visualizations in the geosciences are paramount to aid in educating students about specific earth science phenomena (Kastens et al. 2009), but more research is needed to determine the degree of learning achievable by the addition of visualization tools to more traditional teaching methodologies (Libarkin and Brick 2002).

In previous studies, eye-tracking techniques have provided insight into the effectiveness of 2D and 3D scientific visualizations, such as schematic and labeled diagrams, interpretive signs, and computer animations, to educate about a subject (Coyan 2011). For example, Li et al. (2012) and Chadwick et al. (2010) adapted eye-tracking devices and techniques to establish the relationship of a subject's scanpaths to the accuracy of image interpretations between novices and professionals in biomedical and geographical fields. Along with these two studies, six other significant eye-tracking studies were reviewed in Mayer (2010) that evaluated the effectiveness of four instructional techniques: signaling (the presence or absence of cues), prior knowledge, modality (animation with text or narration), and pacing (fast and slow rates of animation). These techniques, as independent variables, relate perceptual processing to cognitive learning from instructional design (Mayer 2010). These studies also show a relationship between measures of total fixation time and the signaling effect, and prior knowledge effect. Since eye-tracking studies present a relationship between instructional techniques and dependent variables such as total fixation time of relevant POIs, eye-tracking can assist researchers in the testing of hypotheses related to perceptual processing.

Different cognitive processes involved in learning from visualizations can be attributed to spatial thinking, or the ability to problem solve, analyze, and predict patterns through conceptualizing objects and their spatial relationships. The National Research Council (2006) describes the three elements of spatial thinking as distance and dimensionality, understanding the discrepancies in representations, and spatial reasoning. Observers using effective spatial thinking skills when viewing visualizations can use cognitive skills to influence their understanding of particular scientific phenomena. Spatial visualization is one of the most important components in geology education. Geologists and students alike must use spatial visualization learning materials and skills to accurately assess Earth's topography, geologic history pertaining to landscape evolution, and geological 3D structure geometries (Reynolds et al. 2005).

Successful spatial thinking about karst landscapes involves the understanding of the connection between the surface and subsurface environments since the learner is often unable to physically see this connection. Although a person with extensive spatial thinking ability may find it easy to understand the interconnectedness of karst features, the education challenge is to develop karst visualizations for those persons who do not have this spatial thinking ability. Yet, despite the ability of individual elements of a scientific visualization to influence understanding about a subject, prior to this study no research project had investigated the characteristics of karst visualization that have the most influence on observer learning. Thus, adapting eye-tracking techniques to test perceptual processing hypotheses related to spatial visualization in geology education was of particular interest. The effectiveness of interactive geologic visualizations has previously been tested through pre- and post-assessments, interviews, and prior knowledge field assignments (Reynolds et al. 2005), but few studies exist about the adaptation and application of innovative eye-tracking techniques to study visual cognitive learning in geology education. Thus, due to the advancement, accessibility, and effectiveness of eye-tracking techniques, the importance of using eye-tracking as a cutting-edge, powerful tool to study visualizations about karst landscapes is evident.

2.3.2 GIS and GIS Quantitative Analyses of Eye-Tracking Data

This study's overarching goal was to investigate observer's understanding of 2D and 3D, static karst environment visualizations through both qualitative methods and quantitative, post-processing analysis conducted with Geographic Information Systems (GIS) software. GIS uses a combination of software, hardware, networks, procedures, and human resources to create, analyze, and display geographically referenced and spatial information (Longley et al. 2010). The GIS model encompasses spatial data collection, input and correction, storage and retrieval, manipulation and analysis, and output and reporting (Longley et al. 2010). Spatial output data can be in the form of raster or image data or vector data including points, lines, and polygons outputted as shapefiles or feature classes. GIS software is designed to perform the user's particular operational analysis needs. Examples of operations used to analyze GIS spatial input data include coordinate projection, digitization, registration, and statistical analysis (Chang 2011).

Spatial point patter analysis (PPA) is used in a variety of geographic fields focused on understanding the spatial concentration of points and the implications and impact of the location of concentrated points. An example of a geographic field that currently uses PPA to answer research questions related to the location and density of cluster of points is traffic accident analysis. Most of the time, traffic accidents occur in clusters or "hotspots" based on the location of the accidents and the volume of traffic that moves through that location (Xie and Yan 2008). By investigating, the most concentrated "hotspots" of traffic accidents it is possible to take preventative action to avoid high volumes of traffic accidents by increasing police patrol of that location or configuring roadways in a more efficient manner.

Crime event datasets collected by local police departments are another example of geographic spatial data that can be statistically analyzed through GIS technologies to determine clustering patterns and areas of high and low concentration of specific crimes. PPA to define clustered areas of crime data events seeks to "place individual observations into groups that minimize within-cluster variation and maximize between-cluster variation" (Grubesic 2006, p. 96). Through this type of analysis, "hot-spots" can be identified in a geographic study area that highlights areas of high-crime concentration (Levine 1999; Grubesic 2006).

Similarly, Geographic Information Systems (GIS) statistical measures can be used to analyze the spatial raw data outputted by an eye-tracker in the form of an observers' X and Y coordinate fixation gaze points. By using X and Y fixation gaze points, these 2D spatial points are susceptible to "hot-spot" and clustered pattern analyses through two main types of spatial statistical analysis methods: first-order density-based methods and second-order distance-based methods (Xie and Yan 2008). First-order density-based methods include analyses (i.e. standard distance circle analysis and kernel density estimation) that show the main characteristics of point events and determine the mean value of the procedure (O'Sullivan and Unwin 2003; Xie and Yan 2008). Second-order distance-based methods (i.e. nearest-neighbor distance, G function, K function) focus on the spatial interaction structure of point events to develop spatial patterns (Xie and Yan 2008). For this study, kernel density estimation (KDE) was employed to determine areas of high and low fixations on karst visualizations viewed by eye-tracking trial participants. KDE determines density by counting the number of event occurrences in a region that are centered where the user sets the estimation or search radius (O'Sullivan and Unwin 2003). The search radius (bandwidth) is calculated from a feature to the point of interest being processed. By using this approach, it is possible to gather quantitative data that visually describes the concentrated attention of the observer(s) or "hotspots" based upon the density of fixations on each feature of the visualization.

2.4 Summary

Few studies, including North (2011), have explored the role of using informal environmental education to increase protection and conservation of karst landscapes. The literature reviewed herein suggests that eye-tracking is a powerful scientific tool to study cognition and characteristics involved in learning through scientific visual interpretation. Yet, no eye-tracking studies have focused on understanding learning from informal karst interpretative displays and graphics. Using eye-tracking to study informal karst environmental education strengthen the findings of informal karst environmental education studies, thus promoting the acceptance and relevance of scientific environmental interpretation programs to policymakers and educators. In the 21st century, when water resources are increasingly becoming contaminated and karst landscapes are suffering from significant environmental disturbances, the need for studies to establish successful tools to teach the public about the importance of karst is evident. Researchers recognize the need for informal environmental education, yet, the need to study how best to educate through visualizations has, for the most part, been discounted until this study.

CHAPTER THREE: METHODOLOGY

In this study, stationary eye-tracking technology was used to answer research questions related to the learning outcomes of observers when viewing karst-specific instructional visualizations. This research used a triangulated, mixed-methods approach that combined quantitative eye-tracking calculations with knowledge assessments and semi-structured interviews to determine the educational effectiveness of 2D and 3D karst visualizations. Through this approach, the research methodology was composed of 12 pre-existing karst visualizations, 5 new karst visualizations, and the testing of hypotheses related to those visualizations through stationary eye-tracking trials of observers with and without prior geoscience knowledge. The educational effectiveness and learning outcomes of characteristics in the karst visualizations was assessed through pre- and post-knowledge assessments and semi-structured interviews.

3.1 Participant Recruitment for Eye-Tracking Trials

The researchers acquired Institutional Review Board approval in April 2013, as required by Western Kentucky University (WKU). During fall 2013, groups of adult (age 18 or older) participants varying in age and sex, and with and without prior geoscience knowledge were recruited (Figures 3.1 and 3.2). These participants were recruited to investigate differences in how novices and experienced geoscientists observe and comprehend visualizations. In addition, the results of the stationary eye-tracking trials helped to determine how placement and characteristics of focus points in visualizations change attention paths and observer knowledge about the interconnectedness and vulnerability of karst terrains to human impact.

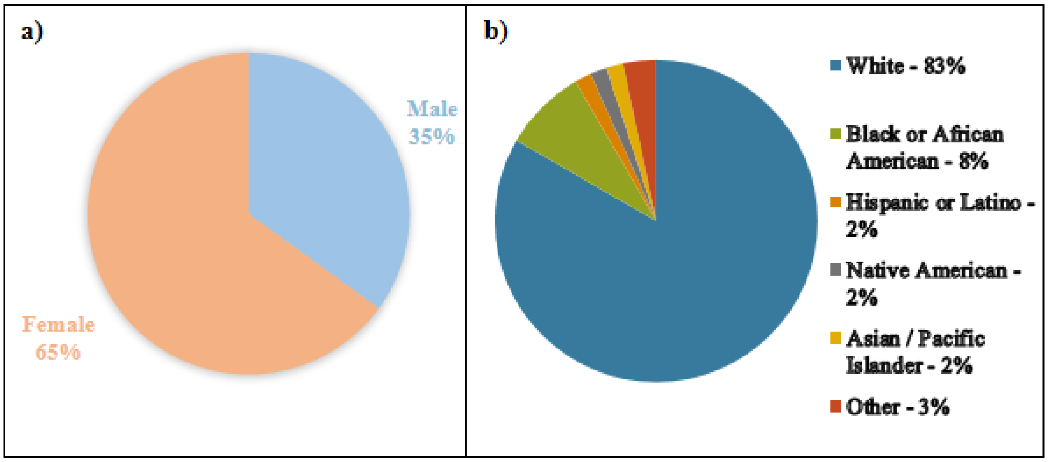


Figure 3.1. Gender (a) and ethnicity breakdown (b) for small group trials.

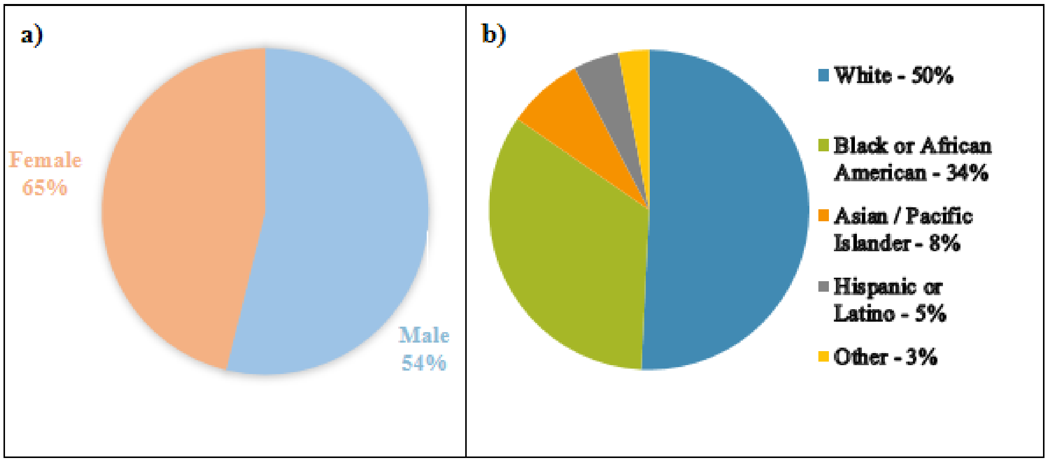


Figure 3.2. Gender (a) and ethnicity breakdown (b) for large group trials.

The recruitment of participants took place on the main and south campuses of WKU with the intention of recruiting a minimum of 10 adults with prior geoscience knowledge and 150 adults without prior geoscience knowledge. This minimum number of participant was determined based on data sets established in previous eye-tracking studies of this nature (see Bouchieux and Lowe 2010; Chadwick et al. 2010; Coyan 2011; Li et al. 2012). Recruitment of individuals was conducted largely through emails to geoscience and education professors that resulted in classroom participant talks and the incentive for class credit or extra credit. WKU’s main and south campuses were chosen as the sample sites due to the location convenience. All minimum numbers of recruitment participants were reached.

3.2 Stationary Eye-Tracking Trial Setup

After individuals were recruited, they participated in a stationary eye-tracking trial, which required each participant to be presented with the developed visualizations on a computer monitor with on-screen text and/or narration and signaling cues. A stationary eye-tracker, as opposed to a mobile eye-tracker which requires specific invasive, eye-tracker glasses, was set up on the computer monitor to calibrate and record the scan paths and fixations of each observer throughout their viewing of the karst visualizations. The stationary eye-tracker used in this study was the Tobii X2-60 Eye Tracker (Figures 3.3 and 3.4). This device was chosen based on similar models used in previous geoscience eye-tracking visualization studies, its data point collection speed at 1/60th of a second, and its’ versatility to magnetically attach to any computer monitor.

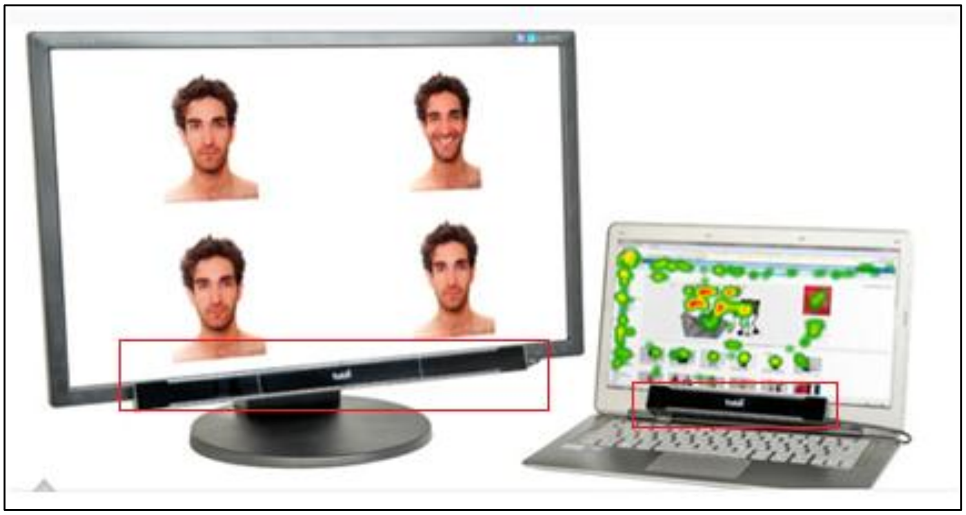


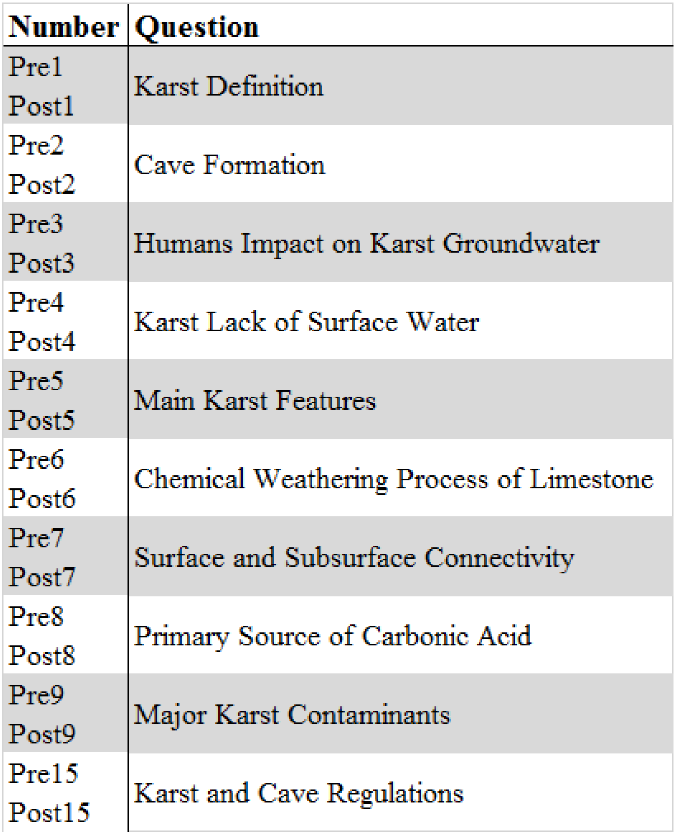
Figure 3.3. Tobii X2-60 Eye Tracker as highlighted in red rectangles.
Source: tobii.com (2014).

Figure 3.4. Participant using the Tobii X2-60 Eye Tracker
Source: theverge.com (2014)

Before participating in stationary eye-tracking trials, participants were provided with an implied informed consent form and offered descriptions of the eye-tracking trial’s goals, intended outcome of the collected eye-tracking and survey data, and the informed consent procedures. Participants still willing to complete a stationary eye-tracking trial after reviewing the consent form were given a knowledge pre-assessment that was comprised of 12 knowledge questions and 6 additional demographic and opinion questions that asked about the participants perspectives on karst environments and prior experiences in geoscience and karst education (see Tables 3.1 and 3.2 and Appendix A). Mayer (2010) and Clark and Libarkin (2011) revealed that written answers to open- and close-ended questions that are scored using a rubric are the most effective cognitive assessment tool in eye-tracking and geological conception studies. Thus, during this study cognitive knowledge assessments with written answers to open- and close-ended questions were distributed prior to and immediately following the visualization viewings. Closed-ended, multiple choice knowledge questions were based on similar multiple choice questions accessed through the

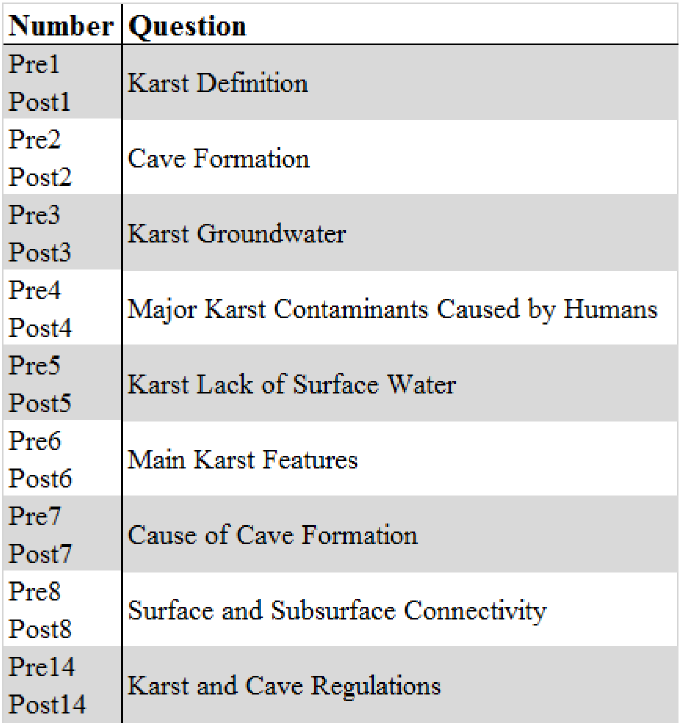
Geoscience Concept Inventory (GCI) and others validated in previous karst education studies (see North 2011). GCI was developed using environmental education theories (i.e. scale development theory, grounded theory, item response theory) as a multiple choice assessment instrument to be used in college-level Earth sciences classrooms (Libarkin and Anderson 2005).

Table 3.1. Pre- and post-assessment question summary for small group experiments.



Number	**Question**
Pre1 Post1	Karst Definition
Pre2 Post2	Cave Formation
Pre3 Post3	Humans Impact on Karst Groundwater
Pre4 Post4	Karst Lack of Surface Water
Pre5 Post5	Main Karst Features
Pre6 Post6	Chemical Weathering Process of Limestone
Pre7 Post7	Surface and Subsurface Connectivity
Pre8 Post8	Primary Source of Carbonic Acid
Pre9 Post9	Major Karst Contaminants
Pre15 Post15	Karst and Cave Regulations

Table 3.2. Pre- and post-assessment question summary for large group trials.



Number	Question
Pre1 Post1	Karst Definition
Pre2 Post2	Cave Formation
Pre3 Post3	Karst Groundwater
Pre4 Post4	Major Karst Contaminants Caused by Humans
Pre5 Post5	Karst Lack of Surface Water
Pre6 Post6	Main Karst Features
Pre7 Post7	Cause of Cave Formation
Pre8 Post8	Surface and Subsurface Connectivity
Pre14 Post14	Karst and Cave Regulations

After the participant completed the pre-assessment, he/she was directed to sit in front of a computer monitor with a stationary eye-tracker attached to view a karst visualization determined by the phase of stationary eye-tracking trial he/she was participating in (Fig. 3.4). First, the eye-tracker completed a calibration procedure to calibrate to the participant’s eye movements. Next, the participant was presented with visualizations on the computer monitor and viewed the visualizations without time constraints. He/she was able to click SPACE bar after viewing the visualization to indicate he/she was ready to move on to the next step of the trial. While the participant viewed the visualization, the trial proctor sat on the other side of a wall divider (Figure 3.5a) or on the opposite side of a table (Figure 3.5b) to view a live feed of the participants’ eye movements and position with the eye-tracker.

Figure 3.5. Trial setup at WKU. a) Main Campus Geocognition Lab, b) South Campus.

After viewing the karst visualizations, participants took a knowledge post-assessment similar to the knowledge pre-assessment and were also asked to participate in a semi-structured interview. These semi-structured interviews were used to solicit feedback from the participant regarding the experiences of the participant when he/she was presented with the visualizations and his/her life experiences involving karst environments. In addition, the semi-structured interviews incorporated questions regarding which visualization the participant found to be the most effective, engaging, and informative. Semi-structured interview questions included:

1. What do you believe the visualizations were trying to teach you about?
2. What were the different karst landscape features and/ or events that were happening in each visualization?
3. What is the difference between the 1st and 2nd visualization?
4. Which way was the water flowing in the visualizations?
5. How did the water enter the cave system?
6. Do you believe one visualization was more helpful than the other in determining the way the water was flowing?

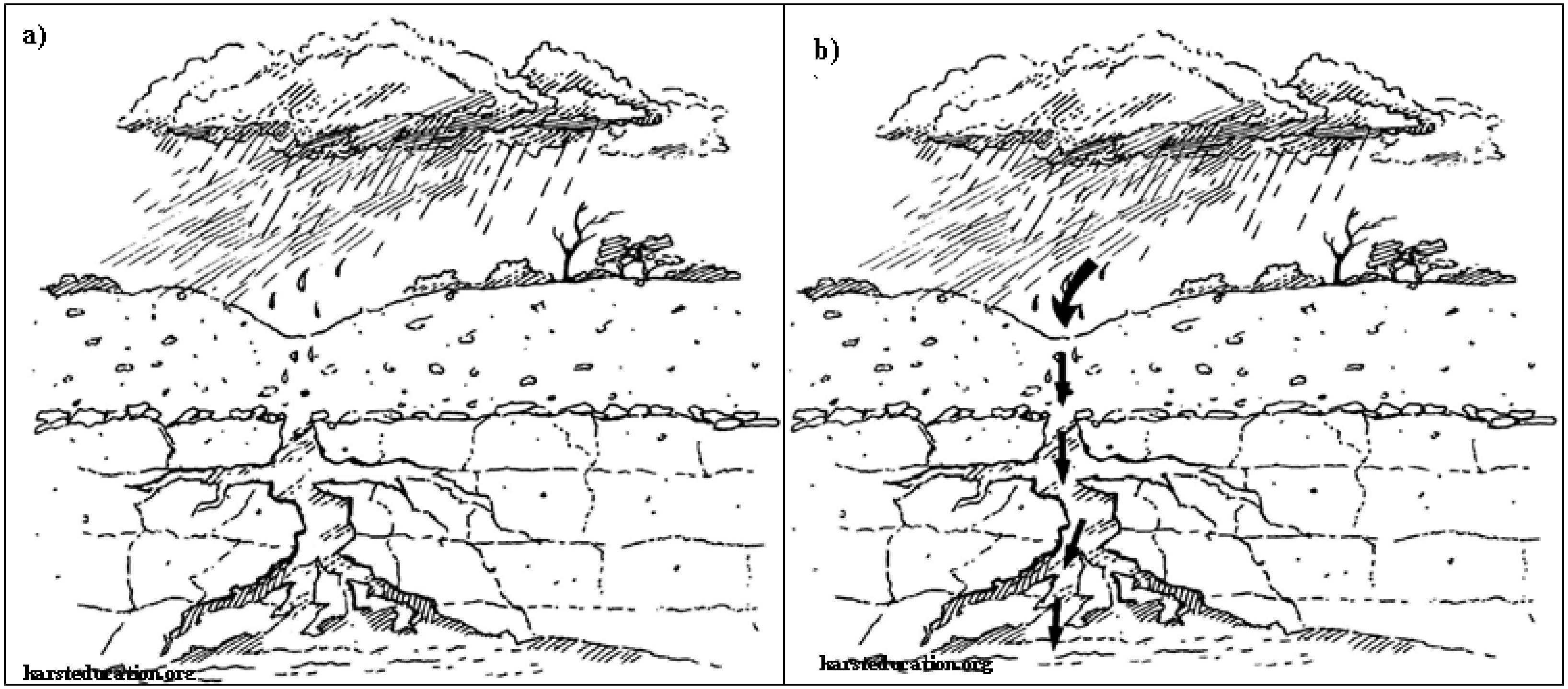
7. Do you have any past experiences with karst and cave environments?
8. What other visual stimuli would you add to a karst visualization to help the general public understand karst landscapes and the importance of karst environments?

3.3 Eye-Tracking Trials

3.3.1 Pre-Existing Karst Visualization Development (Step 1)

To begin this research, a series of pre-existing karst visualizations were gathered from different education curricula through the guidance of previous geoscience eye-tracking studies, input from karst geoscience professionals, and cognitive data related to instructional techniques and theories. By using these resources as a guide, karst diagrams and graphics were gathered and manipulated based on the characteristics and location of visual stimuli to the observers' attention paths. Visual stimuli are items that illicit a cognitive response by the observer to interpret a visualization and can include, color, letters, polygons, squiggles, cubes, faces, etc. (Eng et al. 2005). For this study's purposes, visual stimuli included label placement and content, orientation of the visualization, karst features, scale notation, and color. A graphics artist was employed to manipulate pre-existing karst visualizations in consultation with the researchers in an effort to investigate variation of each of these visual stimuli. In total, in this study, 12 pre-existing karst visualizations with manipulated visual stimuli were used to establish the effectiveness of the visual stimuli to illicit learning. Cognitive response data related to each of these visualizations later guided the development of other karst visualizations with combined visual stimuli. The six main categories of manipulated visual stimuli were organized into small group experiments (SGE) and each experiment consisted of two non-prior geoscience trials (NPGT). The categories of manipulated visual stimuli organized into SGEs included:

1. Arrows versus No Arrows (Figure 3.6)
2. Color with Labels versus No Color with Labels (Figure 3.7)
3. Labels without Color versus No Labels without Color (Figure 3.8)
4. Color without Labels versus No Color without Labels (Figure 3.9)
5. 2D Orientation with Labels versus 3D, Static Orientation with Labels (Figure 3.10)
6. 2D Orientation without Labels versus 3D, Static Orientation Without Labels (Figure 3.11)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karsteducation.org
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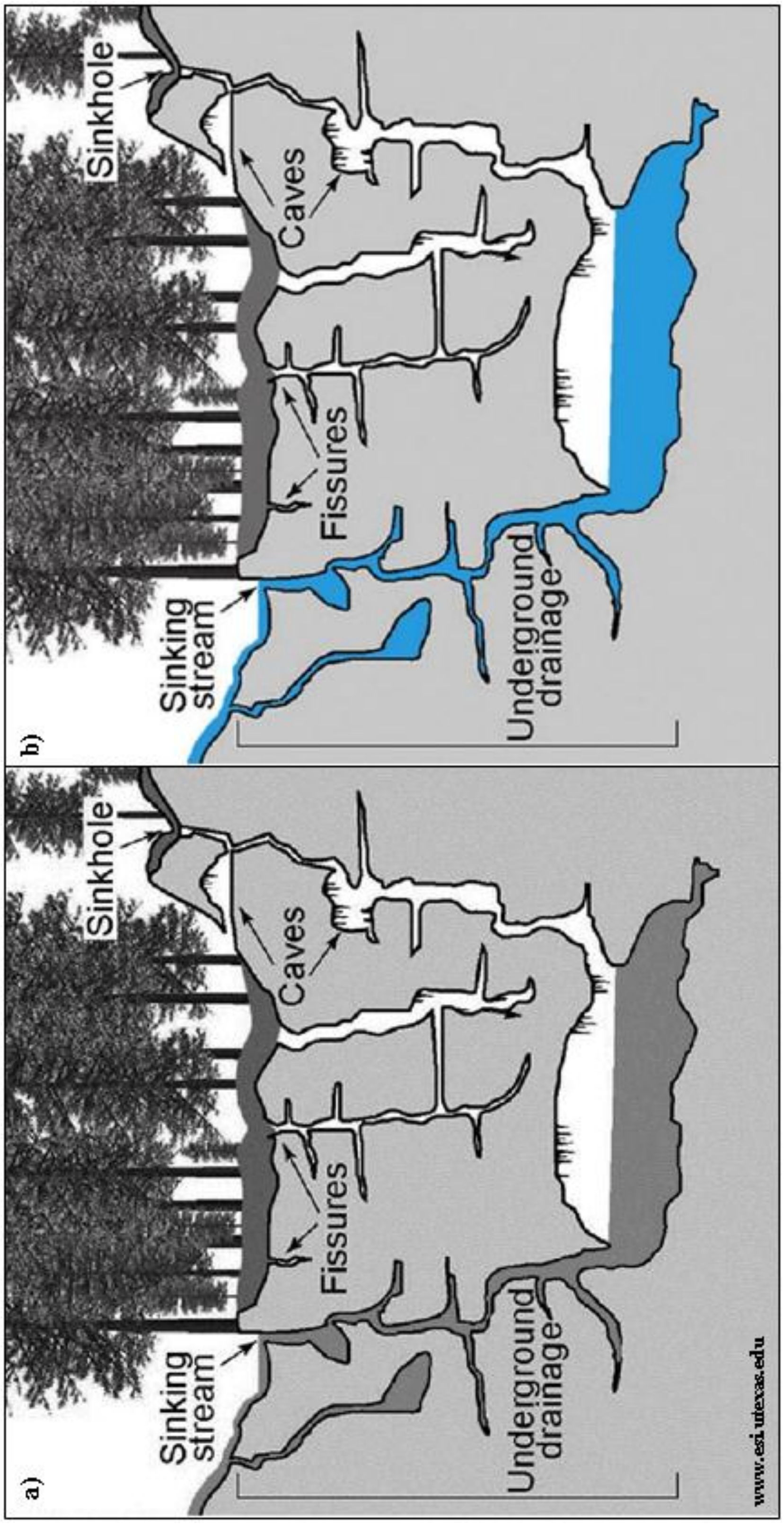
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Sinking stream
Underground drainage
Fissures
Caves
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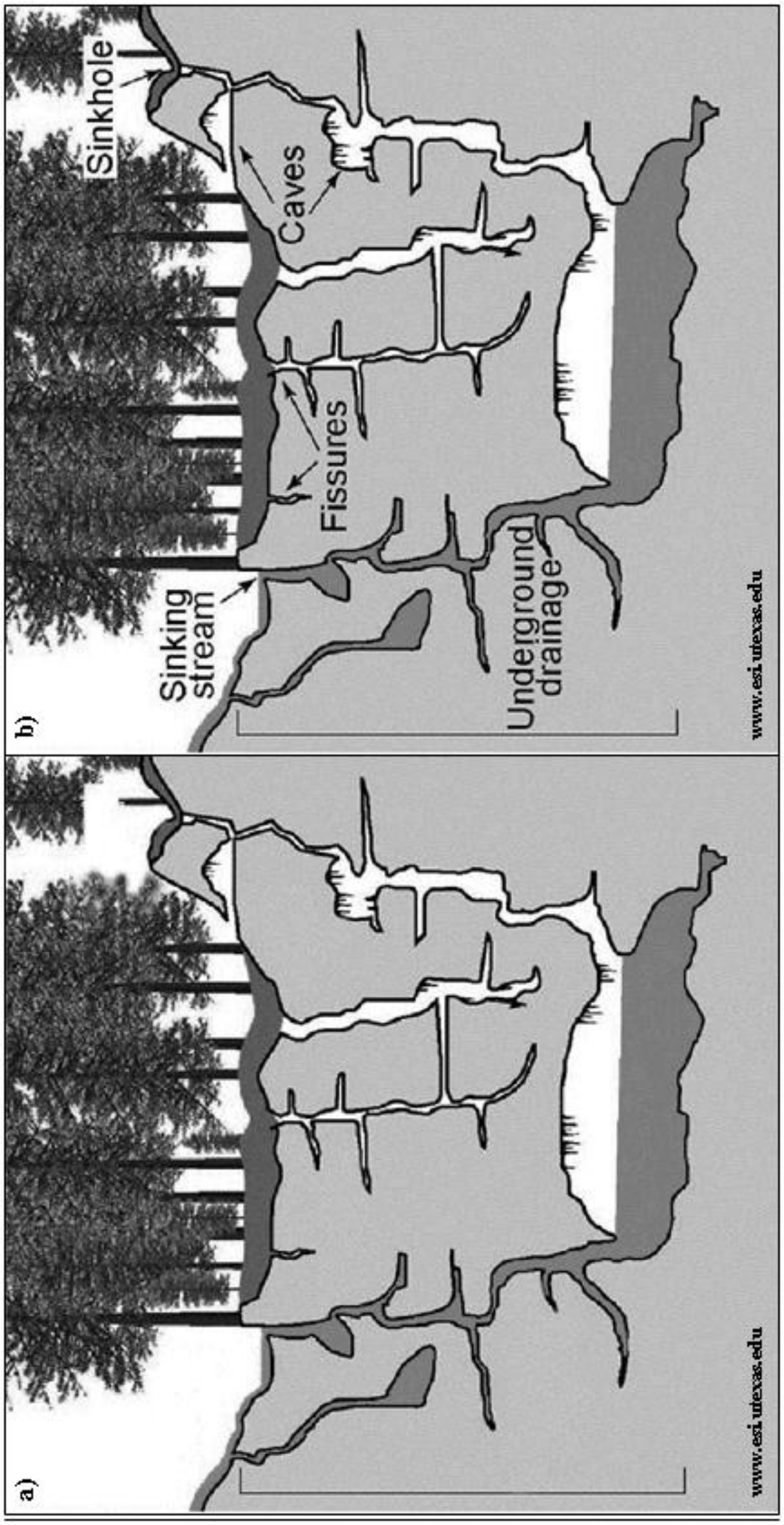
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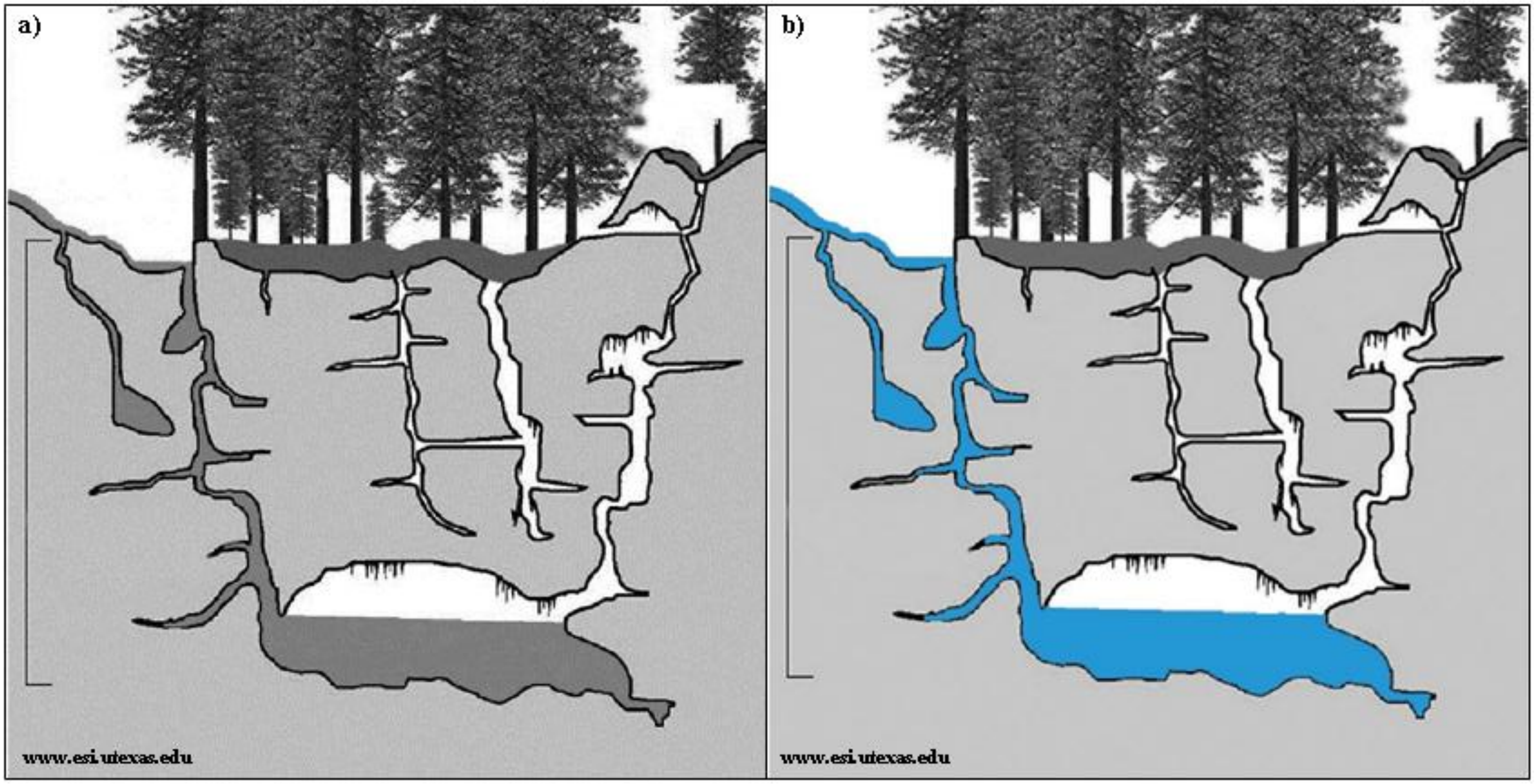
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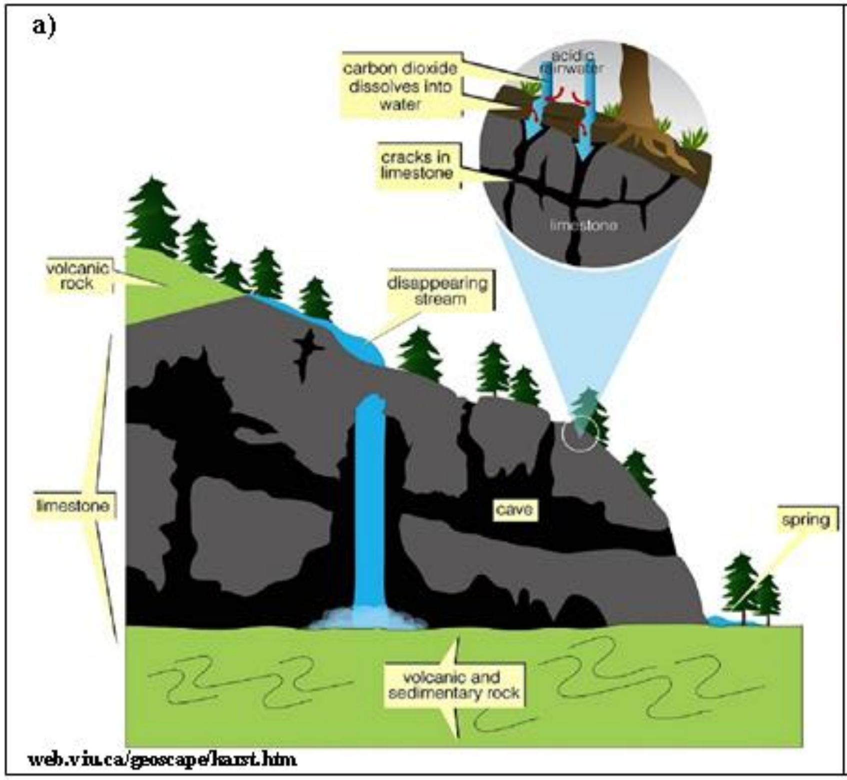

web.viu.ca/geoscape/karst.htm

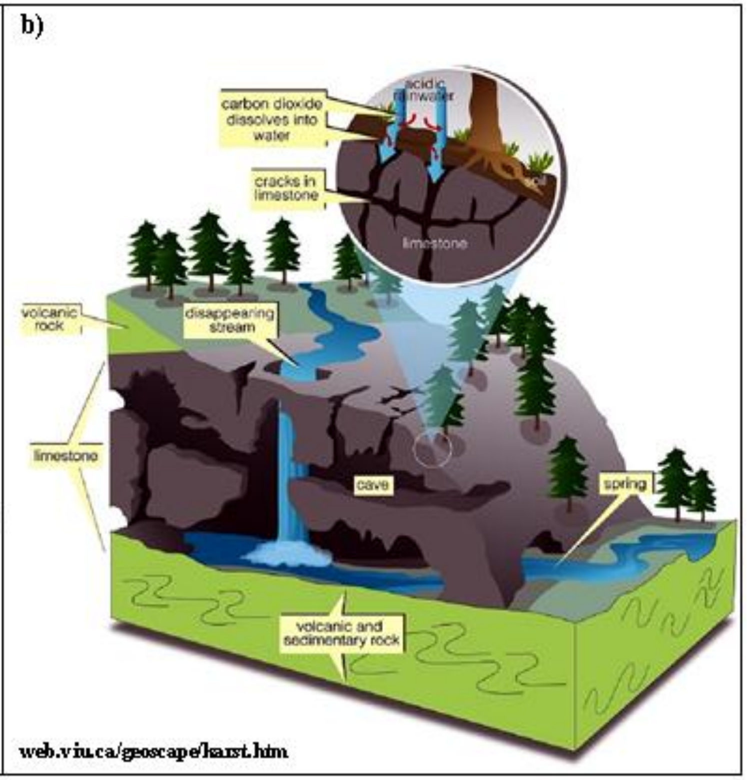

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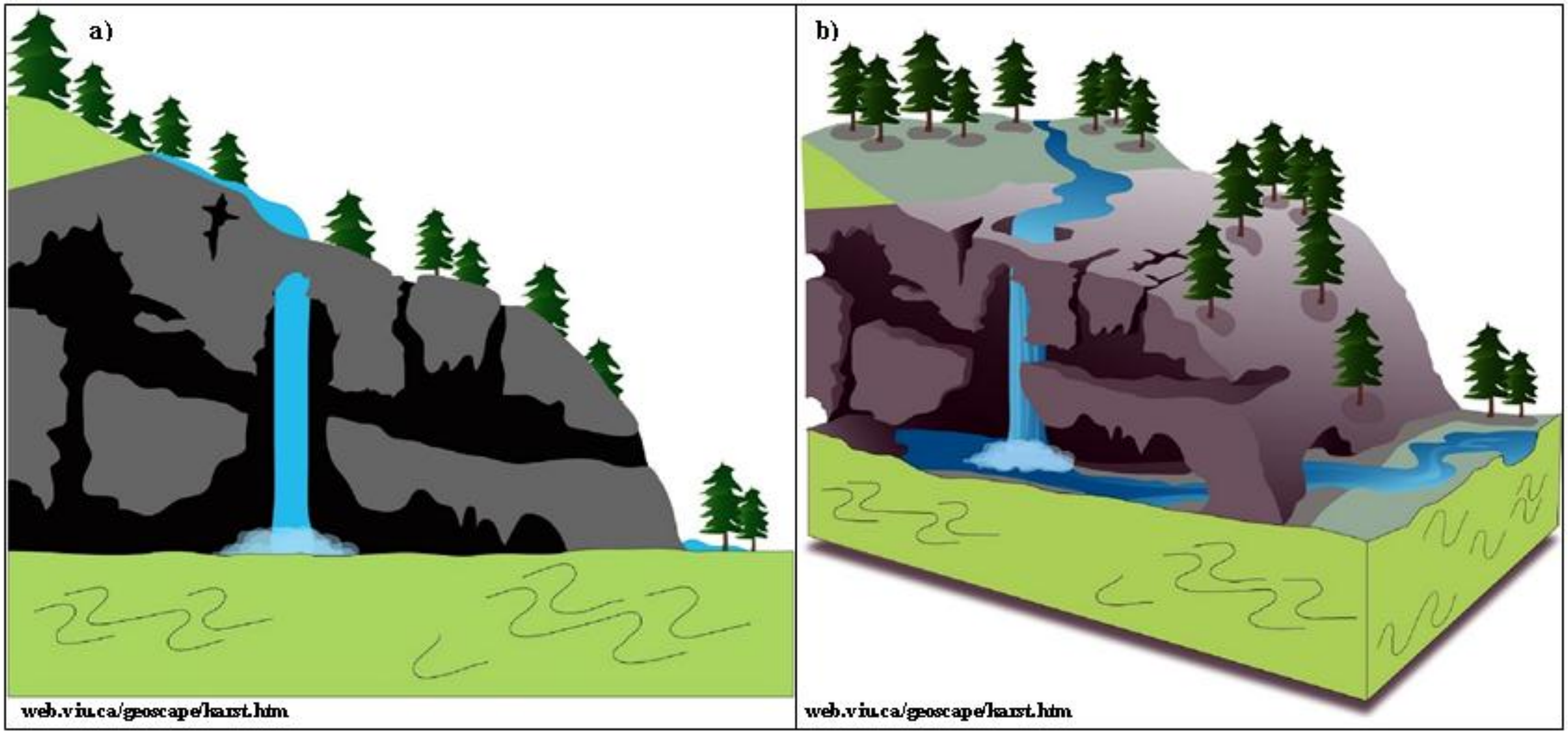
Figure 3.11. 2D orientation without labels versus 3D, static orientation without labels visual. a) shown first in trial



Analysis of the trial eye-tracking measurements and outcomes assessment scores was ongoing and when statistical trends in the dataset were observed, additional pre-exiting karst visualization trials with manipulated visual stimuli were added to pinpoint the most effective characteristics, location of visual stimuli, and orientations of the diagrams for educating about karst landscapes. For instance, after conducting trials 2 through 4, the statistical trends from the eye-tracking results and post-assessments revealed that labels had a large influence on participant' fixation and learning. This influence of labels resulted in the majority of participants' fixations, leaving many parts of the visual unviewed. Thus, trials 5 and 6 were added to isolate and clearly determine the effects of color and orientation as visual stimuli without the influence of labels.

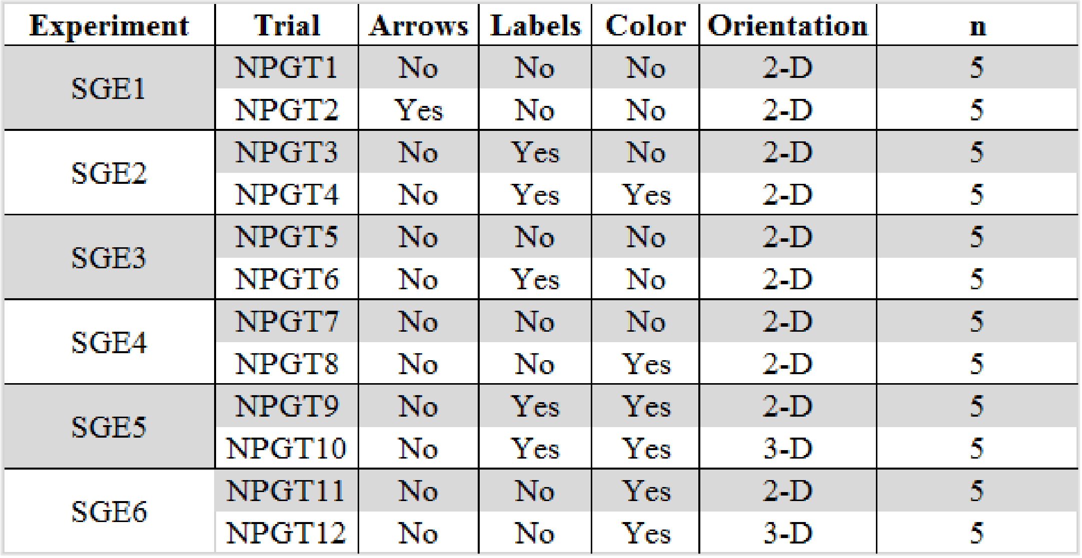
3.3.2 Stationary Eye-Tracking Small Group Experiments (Step 2)

For the first part of this study, small group experiments (SGE) of 10 prior geosciences knowledge participants and 10 participants without geosciences knowledge completed stationary eye-tracking trials with sets of two, 2D karst visualizations to observe. In this phase, the two karst visualizations had the same category of visual stimuli (i.e. label placement, visualization orientation, color, arrows); however, the same category was manipulated differently in the two visualizations. For example, one visualization may have shown a cutaway view of a karst environment while the other visualization may have shown the same karst features with a bird's eye view.

Participants without prior geoscience knowledge completed pre- and post-surveys after viewing the visualizations to establish the learning outcomes of each. Small group experiments were organized into two trials with the same category of visual stimuli tested.

The structure of small group experiments with participants without geoscience knowledge were set up to allow the participants to first take the pre-assessment, view the first karst visualization with or without a category of visual stimuli present in front of the eye-tracker, take the post-assessment, view the second karst visualization with the same category of visual stimuli present in front of the eye-tracker, and finally participate in a semi-structured interview. The process continued until data from 6 small group experiments, with a total of 12 trials of 5 participants each, were collected and statistical analysis showed the most effective visual stimuli of each category (Table 3.3). These stimuli were then added to the visualizations created for the second phase of the stationary eye-tracking trials.

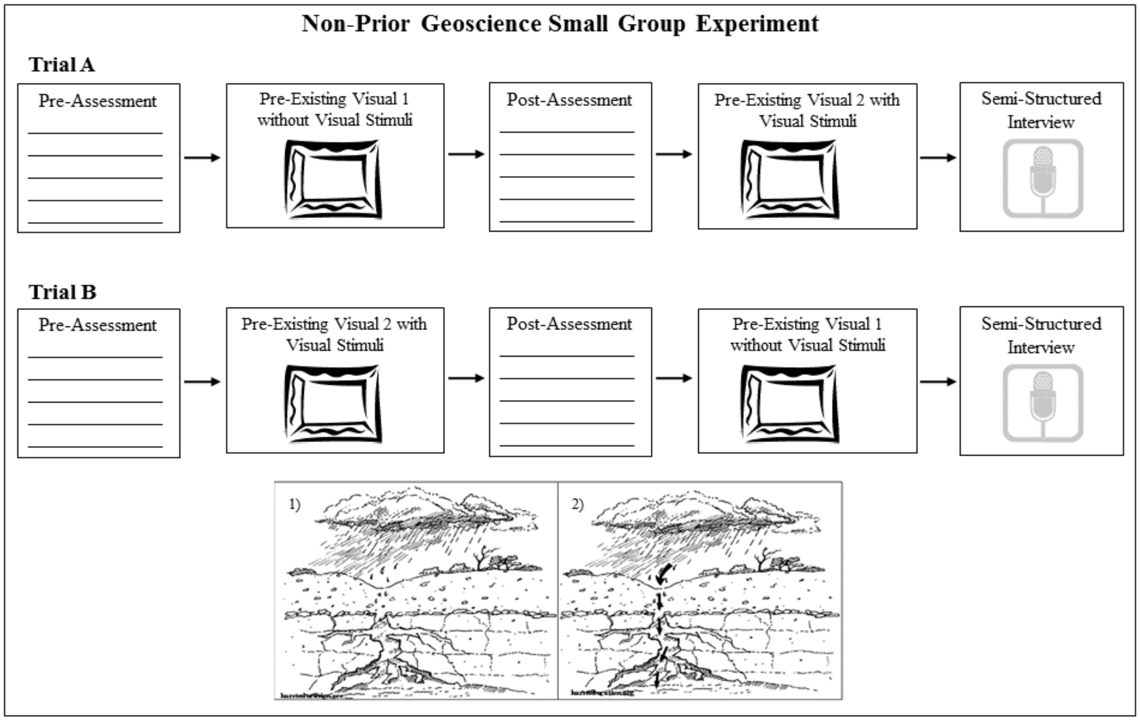
Table 3.3. Small group experiments by trial visual stimuli categories.



Experiment	Trial	Arrows	Labels	Color	Orientation	n
SGE1	NPGT1	No	No	No	2-D	5
	NPGT2	Yes	No	No	2-D	5
SGE2	NPGT3	No	Yes	No	2-D	5
	NPGT4	No	Yes	Yes	2-D	5
SGE3	NPGT5	No	No	No	2-D	5
	NPGT6	No	Yes	No	2-D	5
SGE4	NPGT7	No	No	No	2-D	5
	NPGT8	No	No	Yes	2-D	5
SGE5	NPGT9	No	Yes	Yes	2-D	5
	NPGT10	No	Yes	Yes	3-D	5
SGE6	NPGT11	No	No	Yes	2-D	5
	NPGT12	No	No	Yes	3-D	5

Each of the small group experiments were categorized based on a type of visual stimuli that was manipulated in two trials corresponding to that experiment. This trial structure was set up to analyze the participant’s pre- and post-assessment results along with his/her eye-tracking results after only viewing the first karst visualization with or without a category of visual stimuli present. Performing the assessment and eye-tracking analyses on data from the participants' first visualization allowed for an unbiased data set. The semi-structured interview was recorded after the participant viewed the first karst visualization with or without a category of visual stimuli present and the second karst visualization with or without the same category of visual stimuli. The interview was intentionally conducted after the participant viewed both visualizations to record if the participant noticed a difference between the first and second visualization and if he/she could provide feedback or improvements for both visualizations (Figure 3.12).

Participants with prior geoscience knowledge (karst experts) included geoscience graduate students or professors who specialize in karst landscapes. These participants' knowledge of karst was verified through the completion of a pre-assessment designed to evaluate his/her karst expertise. After the completion of the pre-assessment, these



participants viewed a series of 4 different sets of two, 2D karst visualizations. Each series had a different category of manipulated visual stimuli (i.e. arrows, color, orientation, labels). Participants with geoscience knowledge participated in a semi-structured interview after each set to illicit his/her insights or feedback on each category of visual stimuli and karst visualizations. The sample size of karst experts was small and only the first visualizations were viable to be analyzed through quantitative eye-tracking analyses. Therefore, the results from the karst experts will not be discussed in the "Results and Discussion" chapter of this manuscript; however, trends from this portion of the study will be presented as evidence for future studies to be conducted.

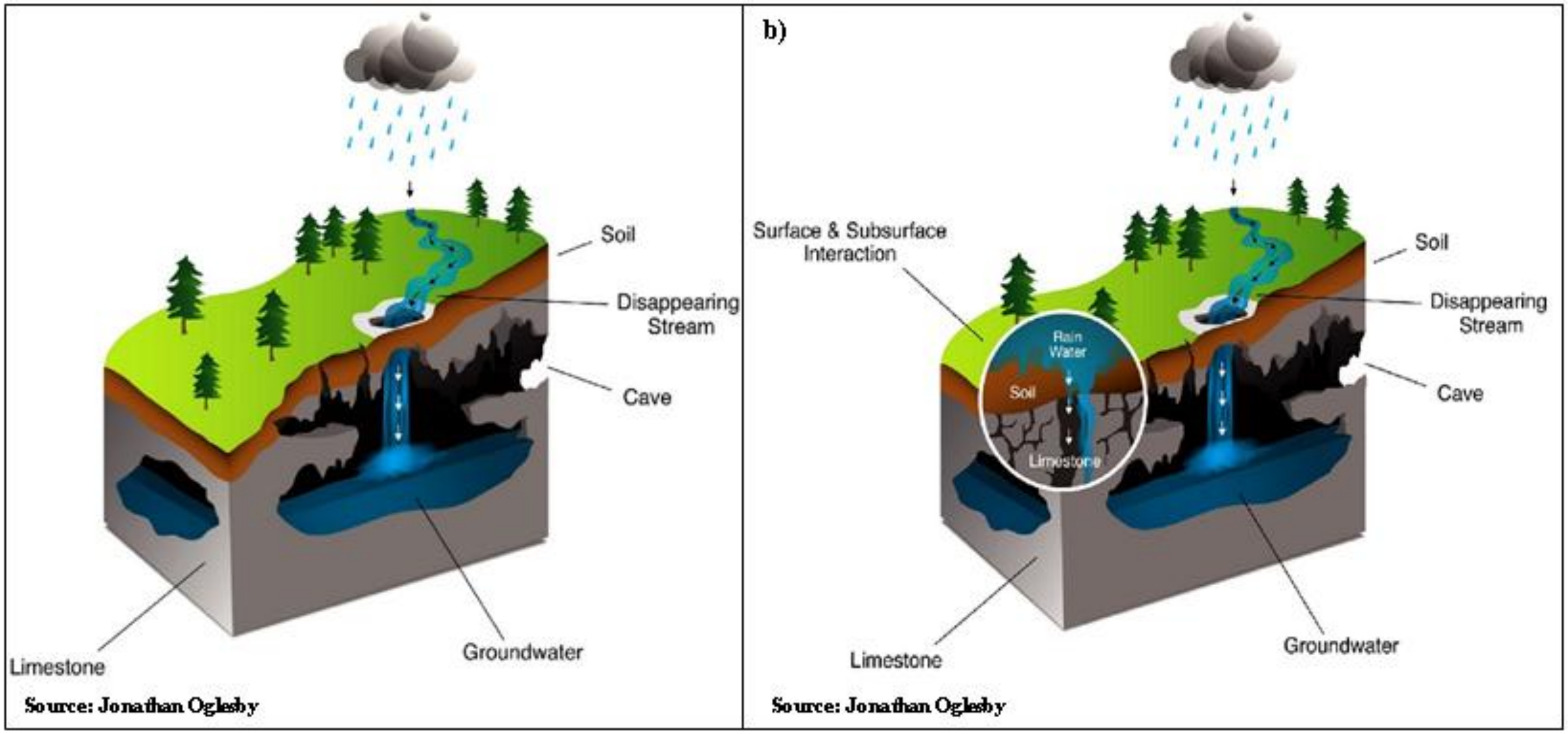
3.3.3 Evolution of New Karst Visualizations (Step 3)

After the completion of the small group experiments and the analysis of trial results revealed statistical trends in the data, a graphics designer was employed to meet with the researchers to review and discuss the results from the small group experiments of novice and professional geoscience persons. From these meetings, a series of new visualizations, which combined the visual stimuli from the small group experiments that most effectively educated about karst landscapes, were created. The development and evaluation of new visualizations was driven be the results from previous trials. The first, 2 trials revealed statistical trends in the dataset and these findings were used to develop 3 additional visualizations, which were tested in 3 more trials. By the conclusion of the non-prior geoscience large group trial (NPGTL) phase, 5 new karst visualizations were developed and tested:

1) Simplistic Baseline Karst Visualization (Figure 3.13),

2) Simplistic Baseline Karst Visualization with Surface and Subsurface Interaction Inset Diagram (Figure 3.14),
3) Karst Visualization with Two Karst Water Sources and Surface and Subsurface Interaction (Figure 3.15),
4) Karst Visualization with Two Karst Water Sources, Surface and Subsurface Interaction, and Contamination Source (Figure 3.16), and
5) Karst Visualization with Two Karst Water Sources, Surface and Subsurface Interaction, and Colored Contamination Source (Figure 3.17).

Figure 3.13. Simplistic baseline karst visualization. a) 1st visual presented in NPGTL1, b) 2nd visual presented in NPGTL1.



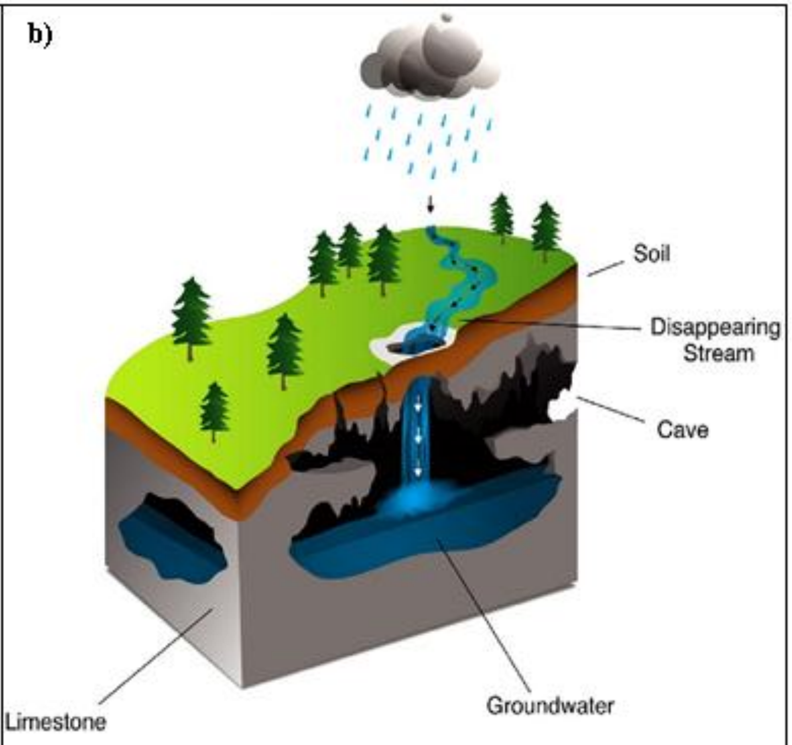
Source: Jonathan Oglesby

Source: Jonathan Oglesby

a)

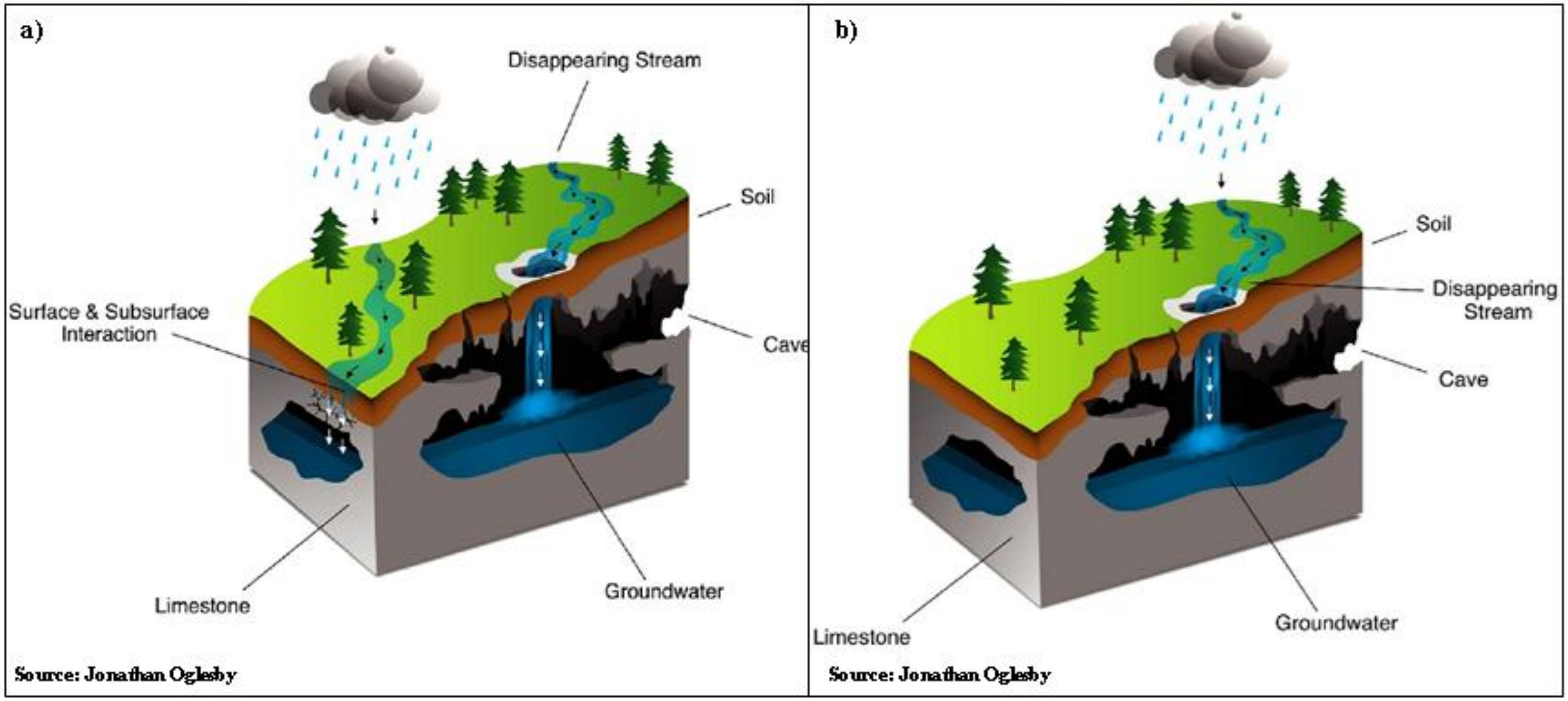
Source: Jonathan Oglesby

b)



Source: Jonathan Oglesby

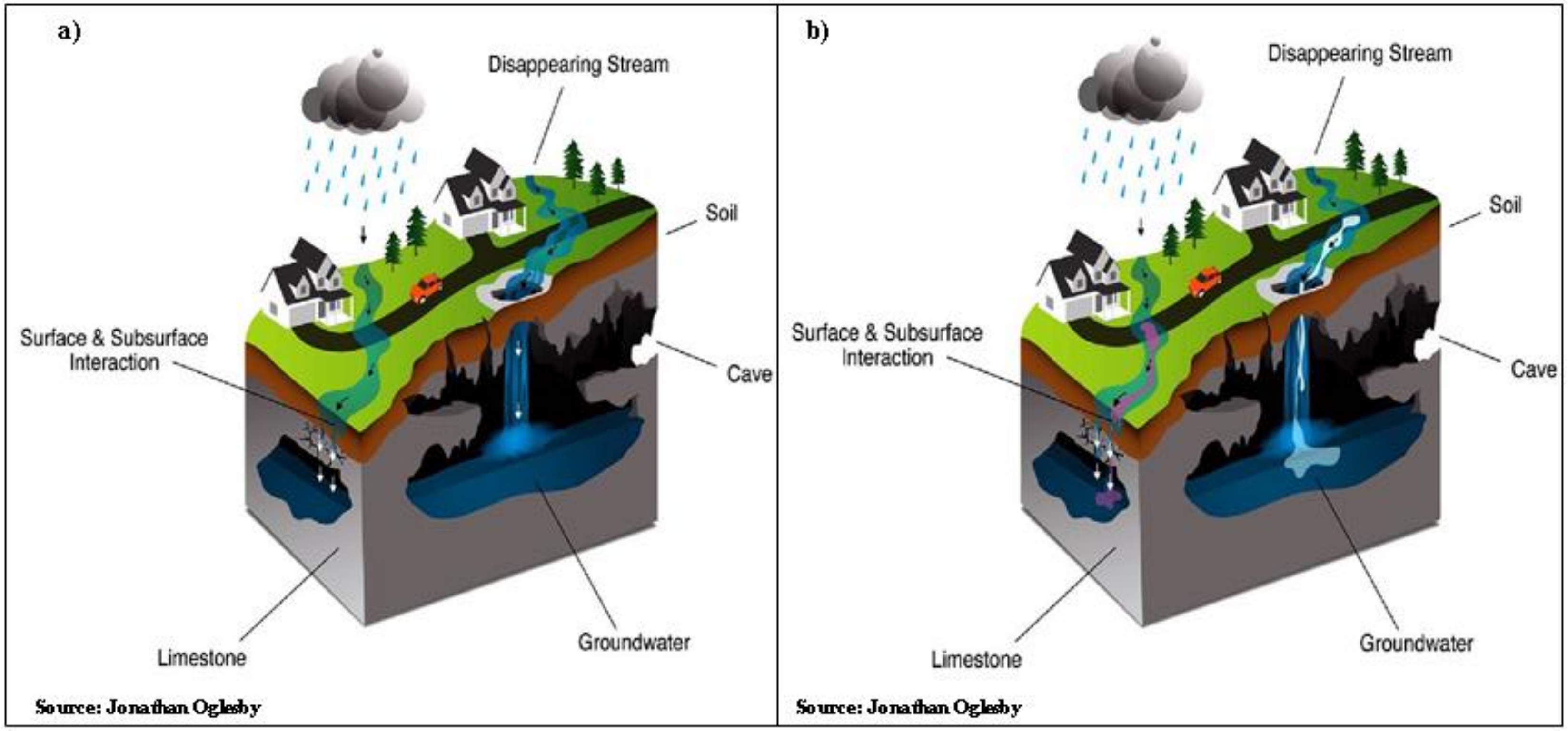
Figure 3.15. Karst visualization with 2 karst water sources and surface and subsurface interaction. a) 1st visual presented in



Source: Jonathan Oglesby

Source: Jonathan Oglesby

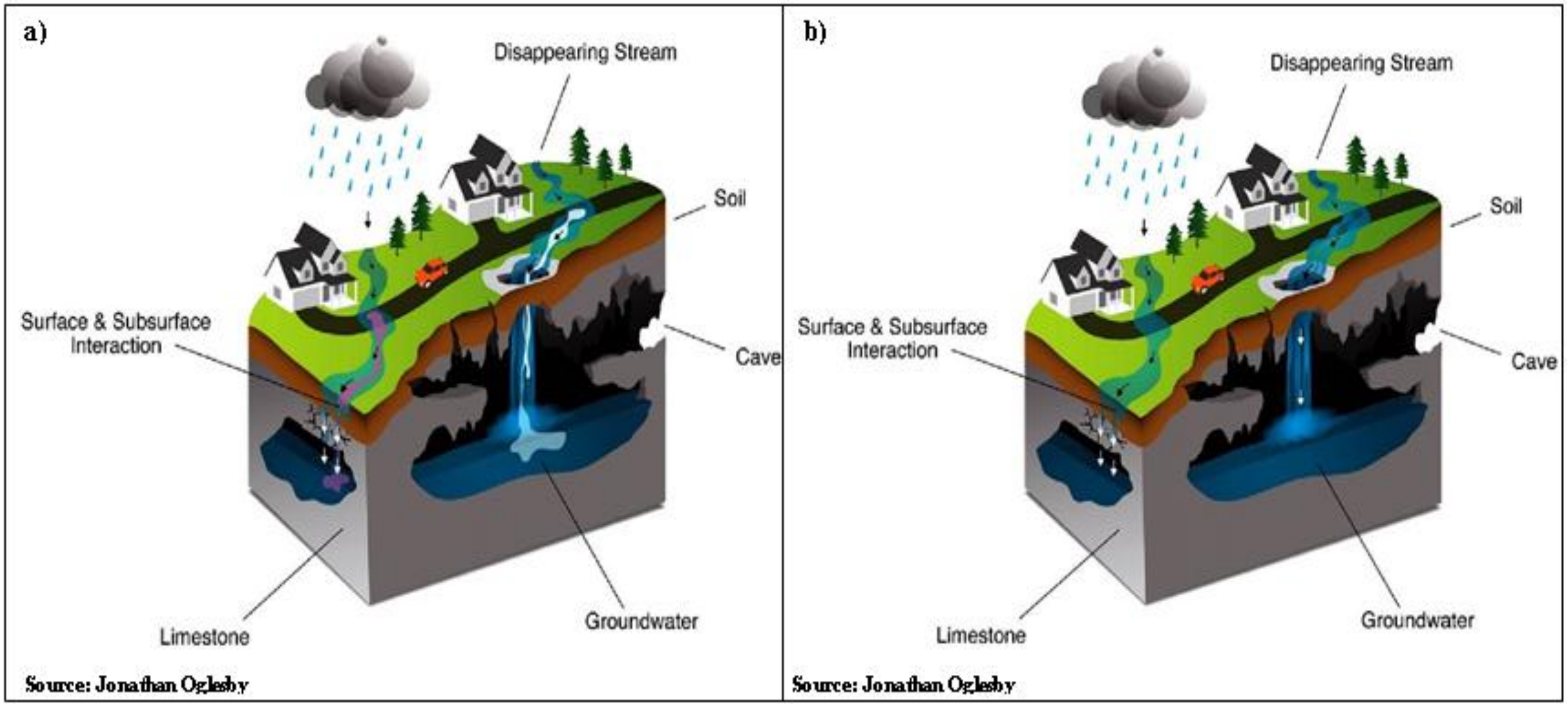
Figure 3.16. Karst visualization with 2 karst water sources, surface and subsurface interaction, and contamination source



Source: Jonathan Oglesby

Source: Jonathan Oglesby

Figure 3.17 Karst visualization with 2 karst water sources, surface and subsurface Interaction, and colored



Source: Jonathan Oglesby

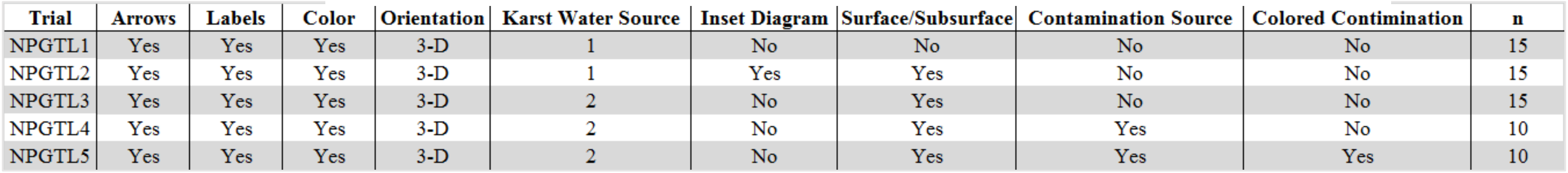
Source: Jonathan Oglesby

While the graphics designer created all of the new karst visualizations that incorporated the most educationally effective visual stimuli from the small group trial results, the designer also relied heavily on basic graphic design principles during the design process. These principles included using the geometric mean to intentionally draw the participant's attention into the visualization and features represented, the use of negative space to force the participant to observe labels and features (Rand 1985), brand identity that transcended through every karst visualization (Wheeler 2012), and taking a minimalistic approach to keep the visualizations as simple as possible to keep the participant's attention focused on the key elements of the visualization (Fishel 1999).

3.3.4 Stationary Eye-Tracking Large Group Trials (Step 4)

In the large group trial phase, 65 participants without geoscience knowledge participated in 5 trials with the latest developed karst visualization: 3 trials composed of 15 different participants and 2 trials composed of 10 different participants. In these large group trials, participants viewed the developed visualizations that combined the most effective visual stimuli from the small group experiments (Table 3.4). Each visualization in the large group trials had multiple colors displayed on the graphic; therefore, each participant took a red-green color vision assessment before the trail began. The red-green color vision assessment was adapted from colourvision.info and based on the Ishihara Color Test, a color perception test that incorporates colored plates with dots that show either two number or to letters to specifically test for red-green color deficiencies (Ishihara 1917).

Table 3.4. Large group trials by combined visual stimuli categories and features.



Trial	Arrows	Labels	Color	Orientation	Karst Water Source	Inset Diagram	Surface/Subsurface	Contamination Source	Colored Contimination	n
NPGTL1	Yes	Yes	Yes	3-D	1	No	No	No	No	15
NPGTL2	Yes	Yes	Yes	3-D	1	Yes	Yes	No	No	15
NPGTL3	Yes	Yes	Yes	3-D	2	No	Yes	No	No	15
NPGTL4	Yes	Yes	Yes	3-D	2	No	Yes	Yes	No	10
NPGTL5	Yes	Yes	Yes	3-D	2	No	Yes	Yes	Yes	10

The structure of the large group trials with persons without prior geoscience knowledge were set up to allow the participants to first take the pre-assessment, then take the color vision assessment, view a karst visualization with combined visual stimuli, take the post-assessment, view the second karst visualization with a different set of combined visual stimuli, and finally participate in a semi-structured interview. After the trials, significant trends were used to determine the most educationally effective karst visualizations with combined visual stimuli.

To minimize bias in the data set, the trial structure was set up to analyze the participant's pre- and post-assessment results along with his/her eye-tracking results after only viewing the first karst visualization with the combined visual stimuli. The semi-structured interview was recorded after the participant viewed both visualizations (Figure 3.18). The interview was intentionally conducted after the participant viewed both visualizations to record if the participant noticed a difference between the first and second visualization and if he/she could provide feedback for both images.

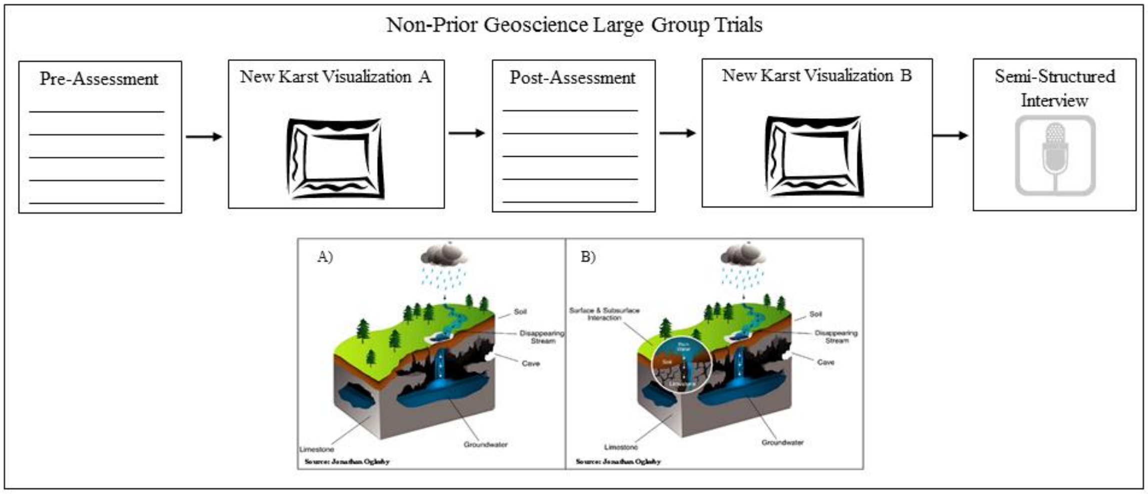
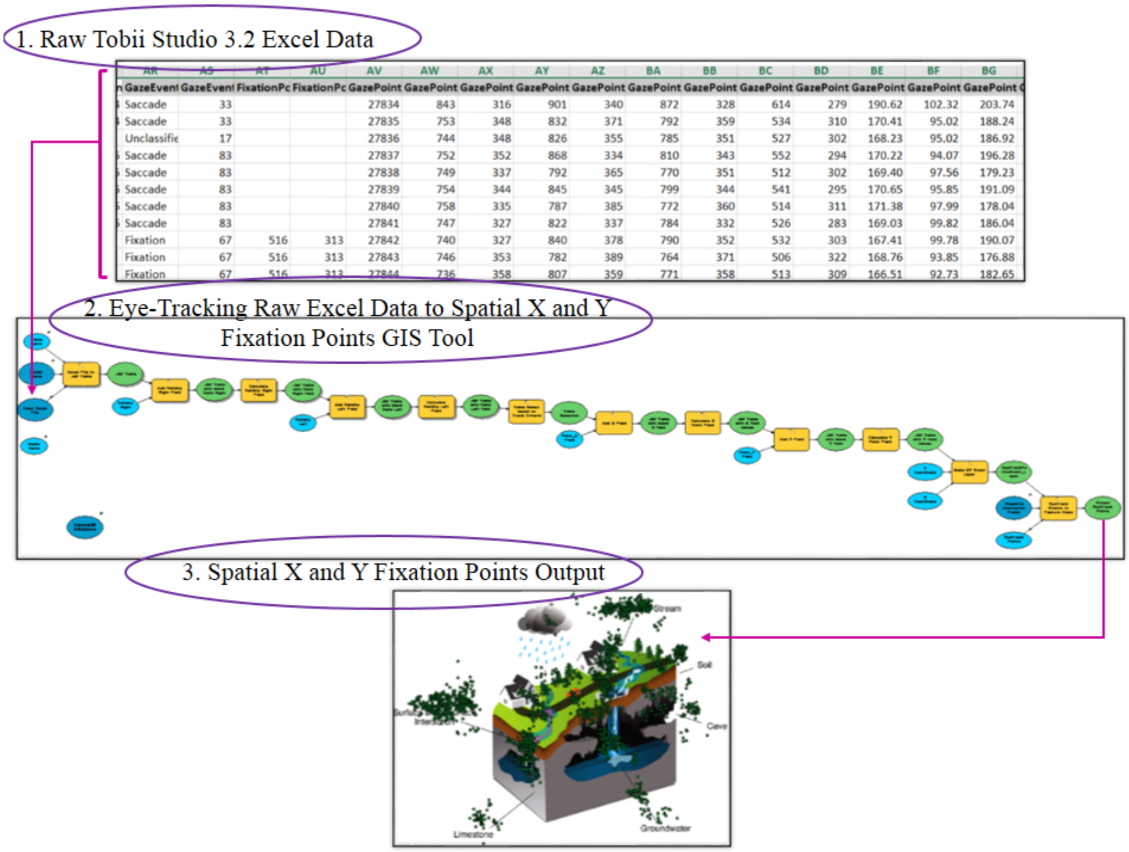


Figure 3.18. Flowchart for large group trials.

3.4 Data Analysis Techniques and Tools

3.4.1 Eye-Tracking Quantitative GIS Analysis

Raw data, including observer's eye movements related to attention paths and fixations, were exported through the eye-tracking software Tobii Studio 3.2. Through eye-tracking software packages such as Tobii Studio 3.2, the researcher could observe the viewer's eye movements in real time, playback the viewer's eye-tracking trial, export the data as an Excel or text delimited file, and create animated gaze plots, heat maps, and clusters. Raw data were processed with ArcGIS for Desktop 10.2 using custom eye-tracking raw data Model Builder tools for further, more advanced statistical analysis. Specifically, in ArcGIS for Desktop 10.2, eye-tracking raw data X and Y 2D gaze coordinates exported from Tobii Studio 3.2 as an excel file were input into the custom EyeTrackExcelToPoints Model Builder tool along with the specific image name to be analyzed. The EyeTrackExcelToPoints tool then extracted all of the relevant raw gaze point data for each participant including X and Y points that corresponded with the specific image data, gaze points with the gaze event fixation type, and the highest validity score of 0 for each eye that was calculated by Tobii Studio 3.2. The output of the EyeTrackExcelToPoints tool was a GIS shapefile containing a participant's X and Y valid fixation gaze points with spatial coordinates to correspond to the image being analyzed (Figure 3.19, Appendix B).



AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD	BE	BF	BG
GazeEvent	GazeEvent	FixationPc	FixationPc	GazePoint	GazePoint	GazePoint	GazePoint	GazePoint	GazePoint	GazePoint	GazePoint	GazePoint	GazePoint	GazePoint	GazePoint
Saccade	33			27834	843	316	901	340	872	328	614	279	190.62	102.32	203.74
Saccade	33			27835	753	348	832	371	792	359	534	310	170.41	95.02	188.24
Unclassifie	17			27836	744	348	826	355	785	351	527	302	168.23	95.02	186.92
Saccade	83			27837	752	352	868	334	810	343	552	294	170.22	94.07	196.28
Saccade	83			27838	749	337	792	365	770	351	512	302	169.40	97.56	179.23
Saccade	83			27839	754	344	845	345	799	344	541	295	170.65	95.85	191.09
Saccade	83			27840	758	335	787	385	772	360	514	311	171.38	97.99	178.04
Saccade	83			27841	747	327	822	337	784	332	526	283	169.03	99.82	186.04
Fixation	67	516	313	27842	740	327	840	378	790	352	532	303	167.41	99.78	190.07
Fixation	67	516	313	27843	746	353	782	389	764	371	506	322	168.76	93.85	176.88
Fixation	67	516	313	27844	736	358	807	359	771	358	513	309	166.51	92.73	182.65

Figure 3.19. Raw Tobii excel data to spatial GIS points workflow.

After the raw gaze points were exported as a GIS shapefile, they were subjected to spatial point pattern analyses. The first spatial point pattern analysis performed on each participant's raw fixation gaze points dataset was kernel density estimation (KDE). KDE estimates density by counting the number of event occurrences in a region that are centered where the user sets the estimation or search radius (O'Sullivan and Unwin 2003). This KDE method was used to determine the ROIs observed by the participant in each eye-tracking dataset through the density of fixation gaze points. To perform the KDE analysis on participants' eye-tracking data, the Kernel Density tool in the Spatial Analyst ArcGIS toolbox was used with an automatic search radius of 27-30 pixels based upon the extent of the visualization and the output cell size set to 1.0. In this study, the KDE search radiuses of the visualizations were calculated based on the approximate average dimensions of the features in the visualizations. In short, by using KDE to analyze X and Y fixations gaze points of the observer, a more quantitative approach to assessing learning outcomes from karst visualizations was.

3.4.2 Knowledge Assessment & Semi-Structured Interview Analysis

Knowledge assessment content was assessed using a scoring rubric (Mayer 2010) and evaluated through a process of content analysis. For closed-ended multiple choice pre- and post-knowledge assessment questions, participants were given a 0 for incorrect multiple choice answers and a 1 for correct multiple choice questions. For open-ended short answer pre-post knowledge assessment questions, participants were given a 0 for an incorrect response, a 0.5 for a partial correct response that demonstrated some knowledge of the question, and a 1.0 for correct response the demonstrated complete knowledge of the question. For the final pre and post assessment regarding participants attitude when asked about the importance of cave and karst regulations, the participants were given a 0 for a negative answer, a 0.5 for a positive answer, and a 1.0 for a positive answer associated with the protection of karst groundwater resources, which was an important element of the visualizations. After the pre- and post-assessments were scored, a sum was calculated for each question. Next, the percentage of participants for each question answer type (i.e. 0, 0.5, and 1) corresponding to each pre- and post-question was calculated and evaluated as percentage change between every pre- and post-question.

Due to the small sample size and the pilot study nature of the small group experiments, statistical tests for significant differences between populations for each trial on the pre- and post-assessments were not tested. However, a Wilcoxon signed-rank sum, two-tailed test was performed on the pre-assessment question 6 (PreQ6) and post-assessment question 6 (PostQ6). This showed significant differences between participants' responses for PreQ6 and PostQ6. The Wilcoxon analysis was performed to validate the sample size of the large group trials. Pre/PostQ6 were selected for the analysis through random number selection of all question numbers. Only one question was randomly selected because prior Wilcoxon analyses were performed on multiple pre- and post-assessments from a chosen large group trial and the statistically significant results were similar for all pre- and post-questions. All Wilcoxon signed-rank sum, two-tailed test were performed using XLSTAT software.

Post semi-structured interviews were transcribed and used as supplementary evidence to support the participants' KDE and pre- and post-assessment results.

CHAPTER FOUR: RESULTS AND DISCUSSION

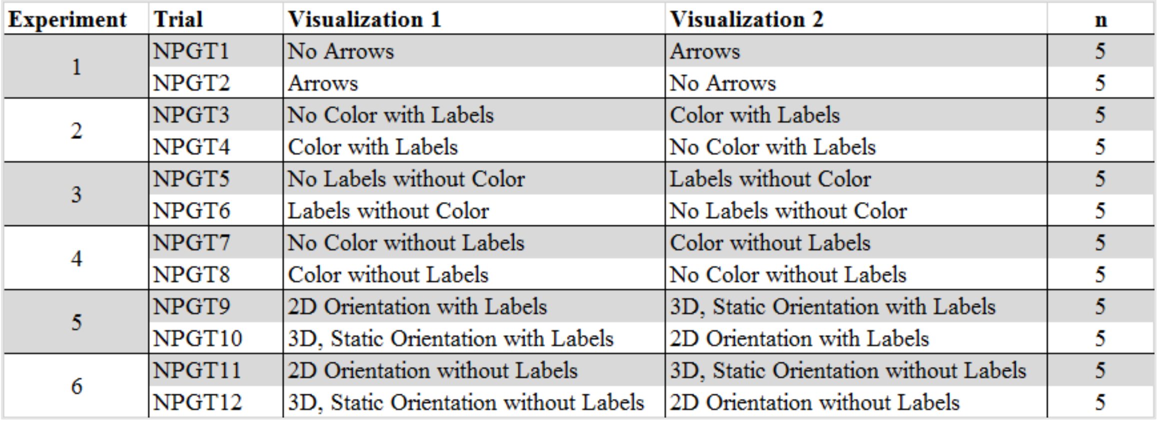
In the 21st century, when cave and groundwater resources are increasingly becoming contaminated and karst landscapes are suffering from other environmental disturbances and destruction, the need for studies that establish successful scientific tools to teach the public about the importance of karst is evident. No eye-tracking studies have focused on understanding formal or informal karst interpretative displays and graphics. Therefore, the main objective of this novel study was to reveal the characteristics of karst visualizations that most effectively improve understanding about the development and interconnectedness of karst features and the relationship of these landscapes to valuable groundwater resources.

The following results of this study, with discussion, will be reported in main sections: Small Group Experiments and Large Group Trials. Under the Small Group Experiments section, there are six subsections that correspond to the visual stimuli category that were manipulated for each set of trials (i.e. Arrows versus No Arrows, Color with Labels versus No Color with Labels). Subsections corresponding to the visual stimuli category are organized as follows: pre- and post-assessment, Kernel Density Estimation (KDE), semi-structured interview, and a discussion of the combined results. Under the Large Group Trials section, there are five subsections that correspond to each new karst visualization. Similar to the small group trial organization, these subsections are organized as pre- and post-assessment, KDE, supplementary semi-structured interview, and a discussion of the combined results. The findings of this study will help to ensure the development of new tools that, with supporting data, are effectively and efficiently communicating about karst and groundwater concepts to non-karst experts.

4.1 Small Group Experiments

Each small group trial was set up like a pilot study to investigate a category of visual stimuli with or without manipulation. Each of these trials had a small number of participants (n=5), with a total of 60 participants collectively, in all of the small group experiments (Table 4.1). For example, for the small group trial with arrows, 5 participants first took a pre-assessment, viewed the pre-existing karst visualization with arrows, took a post-assessment, viewed the pre-existing karst visualization without arrows, and then participated in a semi-structure interview. Please refer to Table 3.1 for an overview of the pre- and post-assessment questions that were used during the small group trial participants.

Table 4.1 Summary of small group experiments.



Experiment	Trial	Visualization 1	Visualization 2	n
1	NPGT1	No Arrows	Arrows	5
	NPGT2	Arrows	No Arrows	5
2	NPGT3	No Color with Labels	Color with Labels	5
	NPGT4	Color with Labels	No Color with Labels	5
3	NPGT5	No Labels without Color	Labels without Color	5
	NPGT6	Labels without Color	No Labels without Color	5
4	NPGT7	No Color without Labels	Color without Labels	5
	NPGT8	Color without Labels	No Color without Labels	5
5	NPGT9	2D Orientation with Labels	3D, Static Orientation with Labels	5
	NPGT10	3D, Static Orientation with Labels	2D Orientation with Labels	5
6	NPGT11	2D Orientation without Labels	3D, Static Orientation without Labels	5
	NPGT12	3D, Static Orientation without Labels	2D Orientation without Labels	5

Due to the small sample size and the pilot study nature of the small group experiments, statistical tests for significant differences between populations for each trial were not tested. However, the trends of the small group experiments, provided direction and indication of the most effective visual stimuli to use in the creation of the new karst visualizations used in the large group trials.

4.1.1 Experiment 1: Arrows versus No Arrows

The KDE results for the participants that viewed the karst visualization with arrows and the participants that viewed the karst visualization without arrows, showed definite regions of interest (ROI) or “hotspots” where the participants spent longer portions of time viewing specific areas of the visualization (Figures 4.1 and 4.2, Appendix D Figures 1 and 2)**.** However, these ROIs varied for each participant group. Participants that viewed the karst visualization without arrows, showed more scattered ROIs throughout most areas of the visualizations, with the most fixations and hotspots occurring around the tree, drops of rainwater near the surface, and the cracks and crevices at the bottom of the subsurface. Conversely, participants that viewed the karst visualization with arrows, had more focused ROIs throughout the visualization with the most fixations and hotspots occurring on the tree, underneath the cloud in the rain, and on each of the five arrows demonstrating the directionality of the rainwater entering the cracks and crevices through the subsurface.

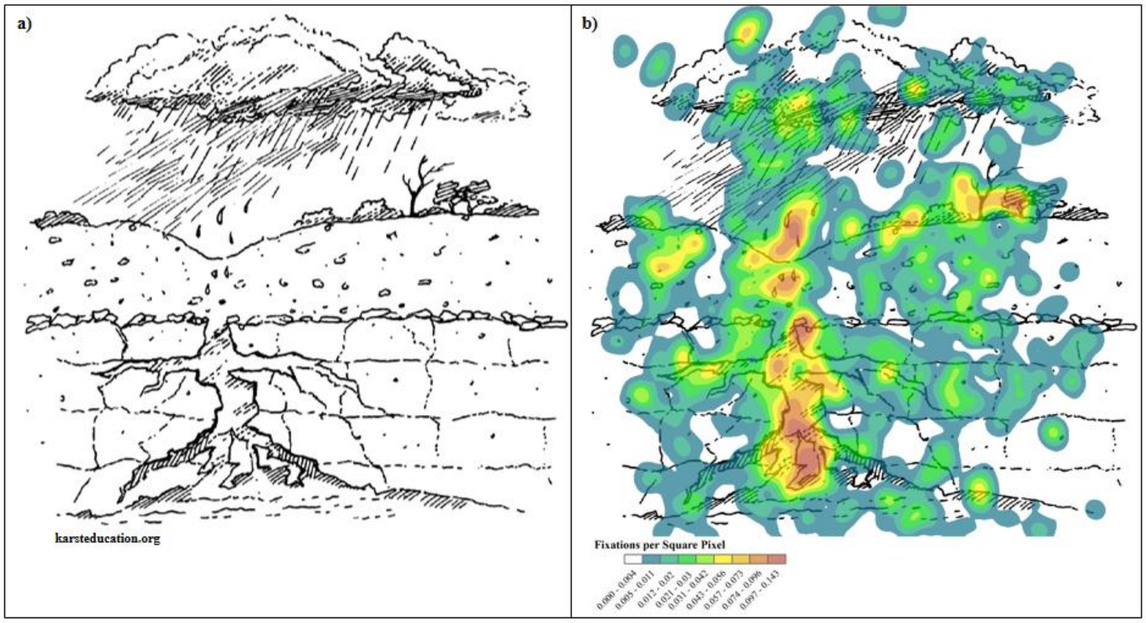


Figure 4.1. a) Karst visualization with arrows b) KDE results of NPGT1 participants

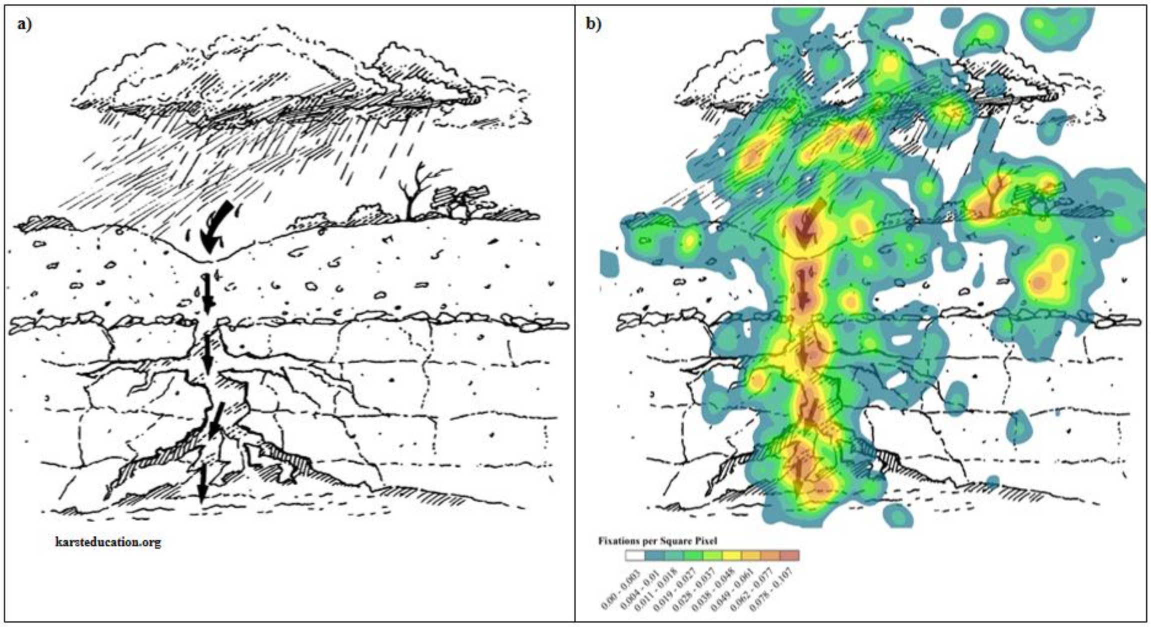


Figure 4.2. a) Karst visualization with arrows b) KDE results of NPGT2 participants

The pre-and post-assessments and semi-structured analyses and quantitative eye-tracking KDE analyses revealed that both sets of visualizations were helpful to participants with no prior karst knowledge of the main features of karst landscape. After viewing either the visualization without arrows or the visualization with arrows, the participants showed improved learning outcomes when defining a karst landscape on PostQ1, listing the main features of a karst landscape on PostQ5, identifying the major contaminants of a karst system on PostQ9, and indicating the importance of karst water resources on PostQ15. The major difference in learning outcomes when comparing the visualization without arrows to the visualization with arrows was seen in regards to PostQ7, which asked about the connectivity between the surface and subsurface (Figures 4.3 and 4.4, Appendix D Tables 1 and 2).

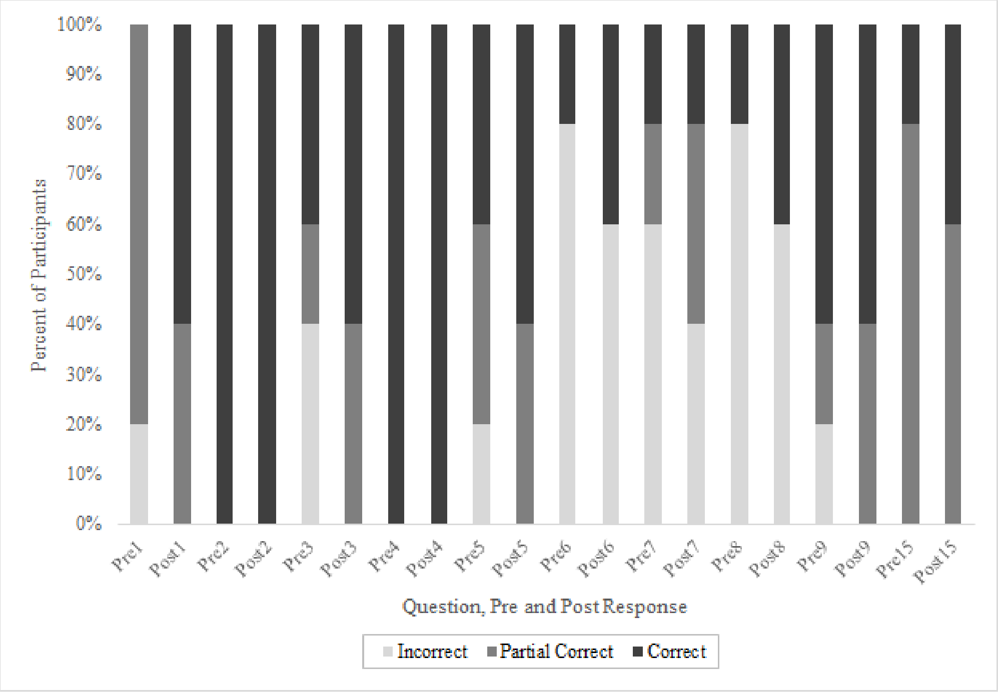
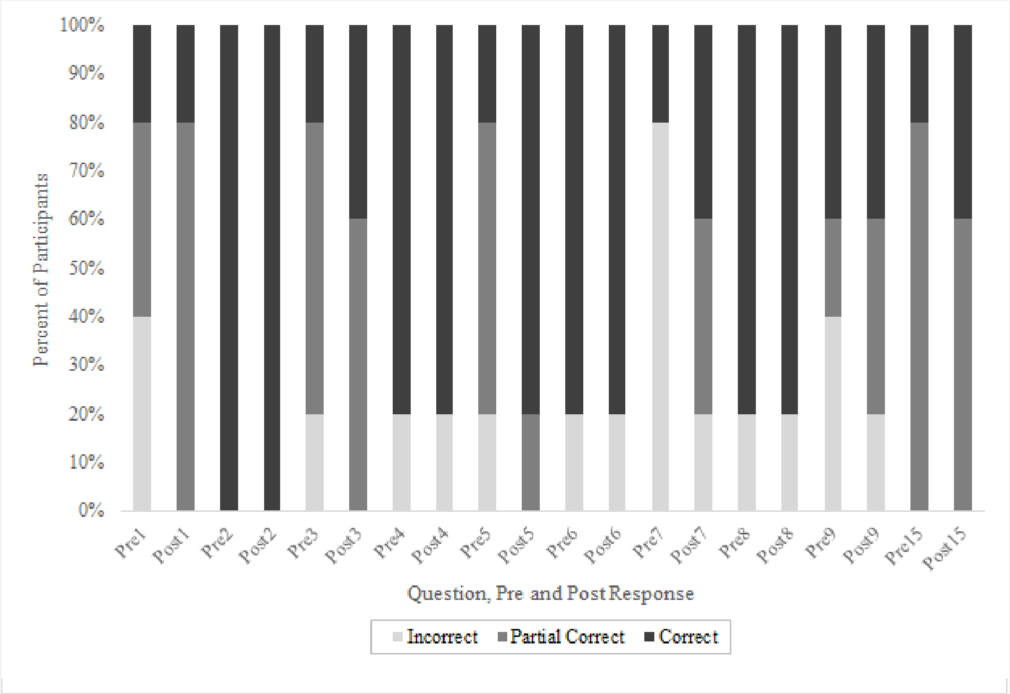


Figure 4.3. Pre- and post-responses of NPGT1 participants.



On PostQ7, after viewing the visualization without arrows, 40% of participants answered partial correctly and 20% of participants provided a full, complete answer. Conversely on PostQ7, after viewing the visualization with arrows, 40% of participants answered partial correctly and 40% of participants answered correctly. These results indicate that better learning outcomes about the connectivity between the surface and subsurface were achieved on the visualization with arrows. These enhanced learning outcomes are also portrayed in the KDE analyses for participants viewing both visualizations. The participants that viewed the visualization without arrows, show more scattered fixations around the diagram, whereas the participants that viewed the visualization with arrows, show more focused fixations and hotspots on each of the five arrows that showed the directionality of water flowing from the surface into the cracks and crevices of the subsurface. Additionally, participants from both trials indicated the importance of arrows in their semi-structured interviews. When asked about which visualization was more helpful, 6 out of 10 participants from both trials indicated that arrows helped. Some example responses included:

1. “Yes, the arrows definitely helped. Helpful to someone that has no experience at all with karst landscapes”
2. “The second one with the arrows would be helpful with little kids”
3. “The arrows could help someone younger that may not understand the concept of gravity”

Also, 6 out of 10 participants from both trials indicated that a tree was a feature of a karst landscape. This result is strengthened even further when reviewing the KDE from both trials. In each of the visualizations, participants’ fixations and hotspots are revealed around the trees on the right side of the visualizations. When asked about improvements that could be made to each visualization, 2 out of 10 participants mentioned the addition of color and 5 out of 10 participants mentioned the addition of labels or descriptions.

Overall, the results from this group of trials demonstrated the educational effectiveness of adding arrows to a visualization in terms of gaining the attention or fixations of the observer to focus specifically on the directional path of the arrows. This finding was also supported in a preliminary study conducted by Griffin and Robinson (2010), which suggested leader lines are effective visual stimuli to link information presented to an observer in a display. Additionally, these findings suggested that less important objects (i.e. trees) presented in a visualization can be a distraction to observers. Both of these findings guided the development of all 5 visualization used in the large group trials. Arrows were added on the surface to show the flow path of rain, disappearing streams, and contaminants. Arrows were also added throughout the subsurface to show the seeping of rainwater and contaminants into cracks and crevices, and to show the directional movement of disappearing stream water moving into the groundwater. Trees were also added to the visualizations with a minimalistic approach to be less distracting. Treetops were intentionally pointed upward to try to draw the attention of the observer upward to the rain cloud or labels in the visuals.

4.1.2 Experiment 2: Color versus No Color with Labels

The KDE results for the participants that viewed the karst visualization with labels but without color and the participants that viewed the karst visualization with labels and color, showed definite regions of interest (ROI) or “hotspots” where the participants spent longer portions of time viewing specific areas of the visualization (Figures 4.5 and 4.6, Appendix C Figures 3 and 4**).** However, these ROIs varied for each participant group. Participants that viewed the karst visualization with labels but without color, show definitive ROIs on every label in the visualization including “sinking stream,” “fissures,” “caves,” “sinkhole,” and “underground drainage”. These participants also had hotspots and fixations on stalactite cave formations and water in the underground drainage area, on cracks and crevices in the subsurface, and on the arrows that corresponded with each label that had arrows.

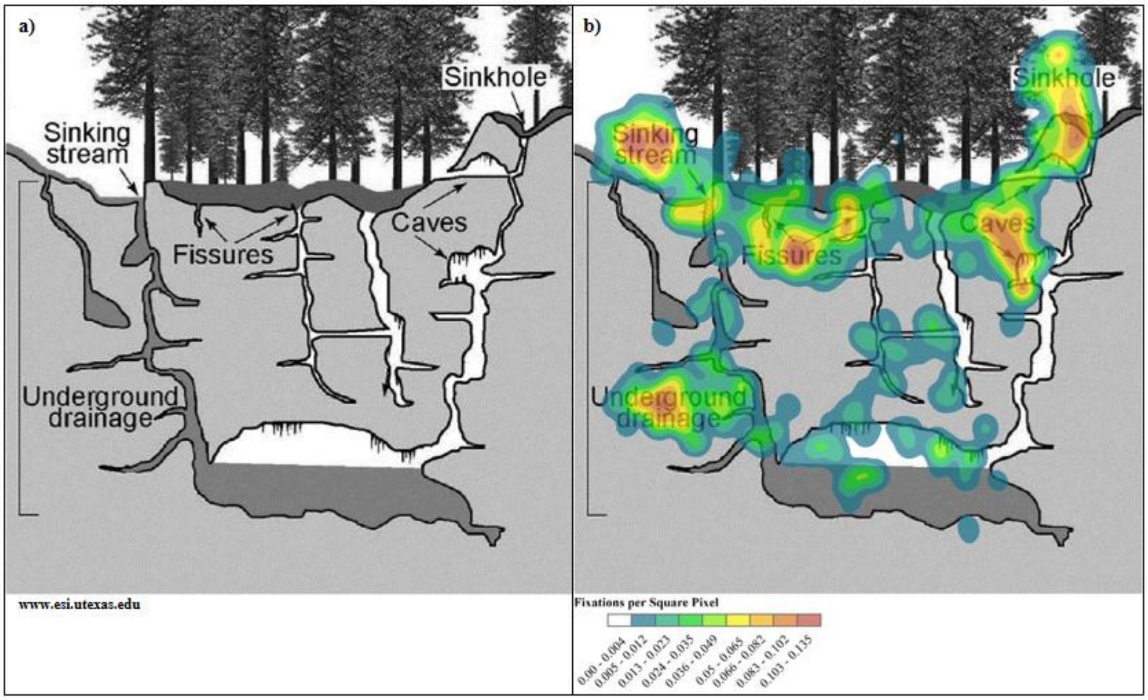


Figure 4.5. a) Karst visual with no color and with labels b) KDE results of NPGT3.

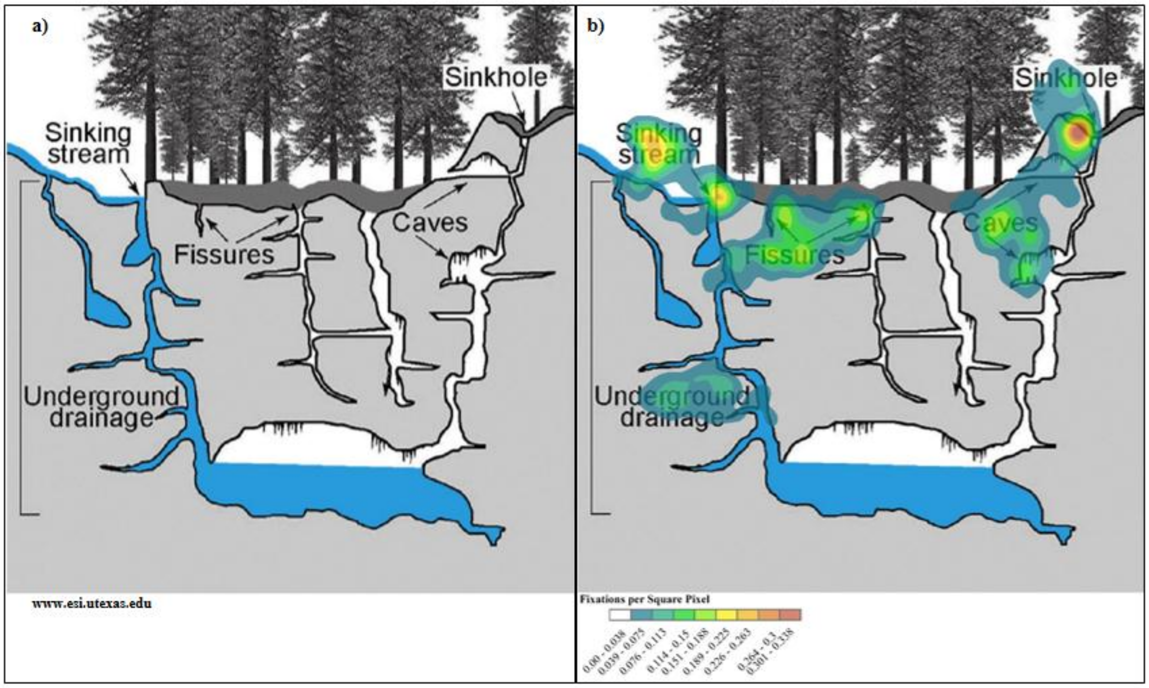


Figure 4.6. a) Karst visual with color and with labels b) KDE results of NPGT4.

Participants that viewed the karst visualization with labels and color, also show ROIs on every label in the visualization including “sinking stream,” “fissures,” “caves,” sinkhole,” and “underground drainage,” and on the arrows that corresponded with each label that had arrows. However, unlike the group that viewed the visualization without color, these participants had the most definitive fixations or hotspots around the “sinkhole” and “sinking stream.” In addition, these participants had little to no fixations on the blue water throughout the visualization and on stalactite cave formations.

Generally, the pre- and post-assessments, semi-structured interview data, and quantitative eye-tracking KDE analyses reveal that both sets of visualizations were helpful to participants with no prior geoscience knowledge to define a karst landscape and its major contaminants. After viewing either the visualization with labels and color or the visualization with labels but without color, the participants had better learning outcomes when defining a karst landscape on PostQ1, discussing the major contaminants of a karst system on PostQ9, and indicating the importance of karst water resources on response to PostQ15 (Figures 4.7 and 4.8, Appendix D Tables 3 and 4).

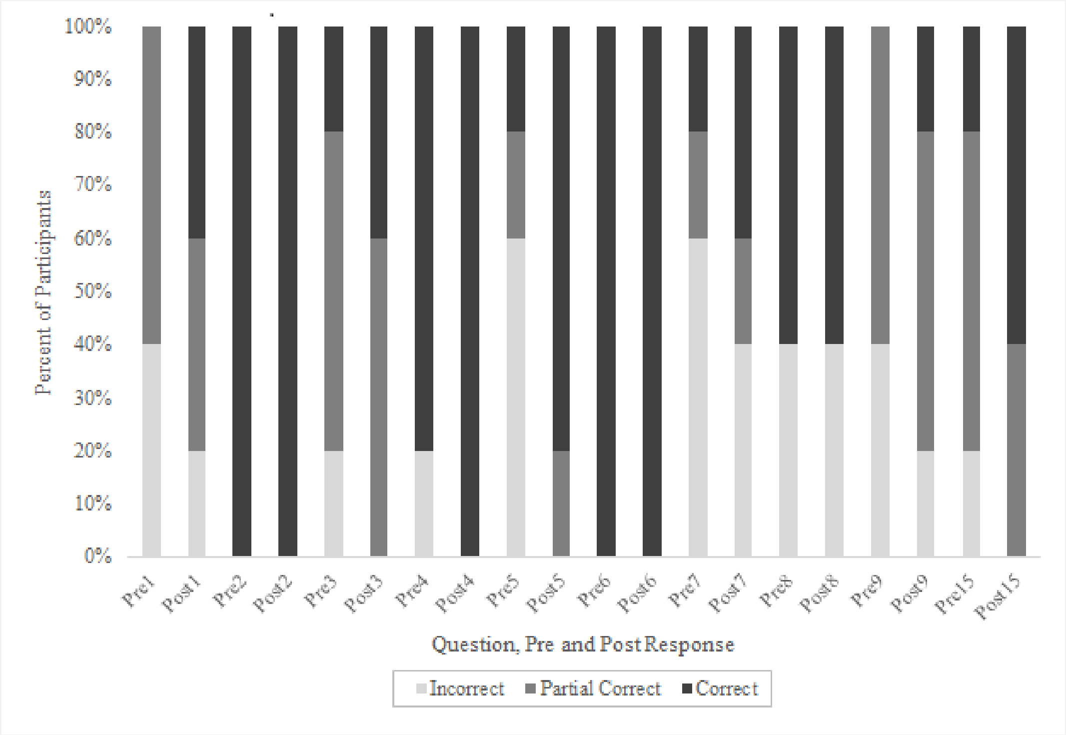


Figure 4.7. Pre- and post-responses of NPGT3 participants.

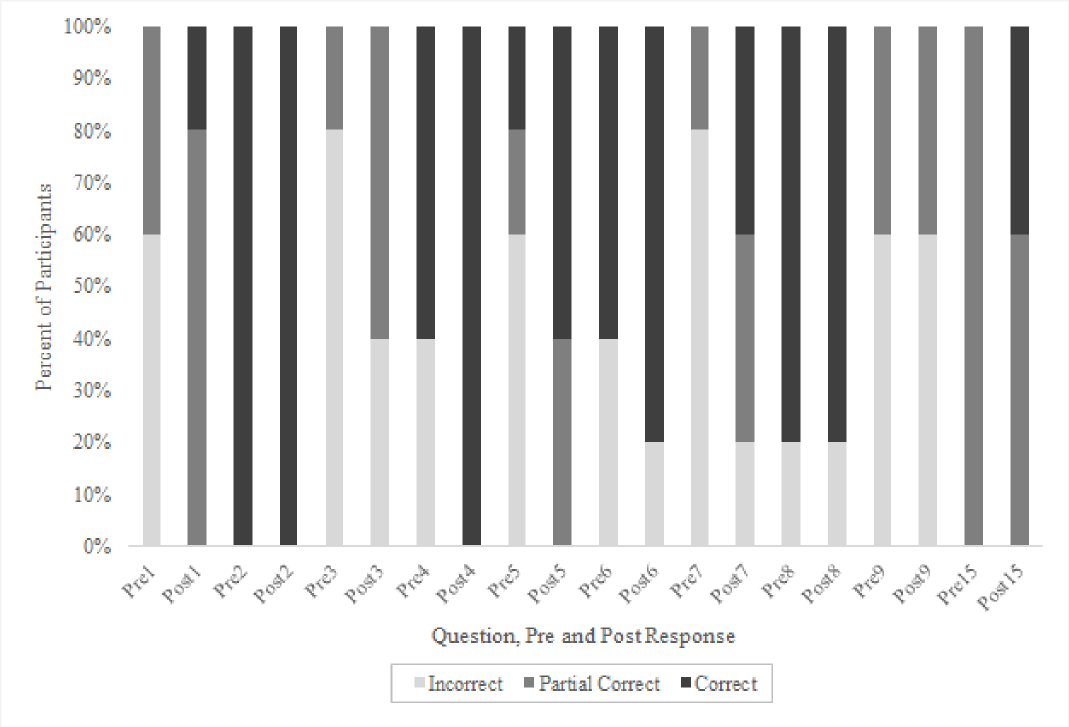


Figure 4.8. Pre- and post-responses of NPGT4 participants.

The major difference in learning outcomes when comparing the visualization with labels and color to the visualization with labels but without color, was on PostQ5, which asked the participants to list the main features of a karst landscape, and on PostQ7, which asked about the connectivity between the surface and subsurface. On PostQ5, after viewing the visualization without color, 20% of participants answered partial correctly and 80% of participants answered correctly. Conversely on PostQ5, after viewing the visualization with color, 40% of participants answered partial correctly and 60% of participants answered correctly. These results suggest that more participants achieved higher learning outcomes after viewing the visualization without color. Additionally, when asked to list the features of a karst landscape out of the total participants that viewed the visualization without color, 4 out of 5 participants mentioned “sinkholes”, 4 out of 5 participants mentioned “caves,” and 3 out of 5 participants mentioned “fissures.” Comparatively, out of the total participants that viewed the visualization with color that were asked to list the features of a karst landscape, 3 out of 5 participants mentioned “sinkholes”, 5 out of 5 participants mentioned “caves” and 2 out of 5 participants mentioned “fissures.” The visualization included “sinkhole”, “caves”, and “fissures” labels in the visualization and, after viewing the KDE analyses for each visualization, it is evident that the participants for both visualizations showed highly concentrated areas of fixations on each of those labels. However, those areas of fixation where more concentrated on the visualization without color, suggesting an explanation for the higher learning outcomes on PostQ5 for that participant trial.

On PostQ7 after viewing the visualization without color, 40% of participants answered incorrectly, 20% of participants answered partial correctly, and 40% of participants answered correctly. Conversely, on PostQ7, after viewing the visualization with color, 20% of participants answered incorrectly, 40% of participants answered partial correctly, and 40% of participants answered correctly. These results indicate that higher learning outcomes were achieved on the visualization with color when participants were asked about the connectivity between the surface and subsurface. These higher learning connectivity outcomes are not easily portrayed through the KDE analysis because the KDE analysis for the visualization with color does not show higher concentration of fixations on the blue color; however, the semi-structured interview responses from each set of participants suggest that 7 out of 10 participants indicated that color was the difference between the two visualizations. Furthermore, when asked about improvements that could be made to each of these visualization, 4 out of 5 participants that viewed the visualization without color first, mentioned an improvement could be made to these visualizations in the form of arrows that showed the directionality and flow of the water.

Based on the results of both of these trials, it was evident that labels had an important role to help observers identify the main features of a karst landscape. Color (especially blue colored water) played an equally important role to help the observer understand the surface and subsurface connectivity of a karst landscape. Therefore, the educational importance of labels and color was dually noted during the development of the 5 karst visualizations used in the large group trials. The results and trends of these trials also helped to guide the direction of other small group experiments; due to the large influence of labels on the participants’ attention, more small group experiments were conducted that removed labels from the visualizations and instead focused on the influence of color and orientation.

4.1.3 Experiment 3: Labels versus No Labels without Color

KDE results for the participants that viewed the karst visualization with no labels or color and the participants that viewed the karst visualization with labels but without color, that participants show definite regions of interest (ROI) or “hotspots” where the participants spent longer portions of time viewing specific areas of the visualization (Figures 4.9 and 4.10, Appendix C Figures 5 and 6). However, these ROIs varied for each participant group. Participants that viewed the karst visualization with labels but without color, show definitive ROIs on every label in the visualization including: “sinking stream”, “fissures”, “caves”, “sinkhole”, and “underground drainage”. These participants also had hotspots of fixations on stalactite cave formations and water in the “underground drainage” area, on cracks and crevices in the subsurface, and on the arrows that corresponded with each label that had arrows. Conversely, participants that viewed the karst visualization without labels or color showed fewer fixations on specific ROIs than participants who viewed the same visualization with labels. Most hotspots or fixations occurred on water entering the cracks and crevices on the left side and the sinkhole on the right side with hotspots also occurring on the stalactites and cracks and crevices throughout the visualization.

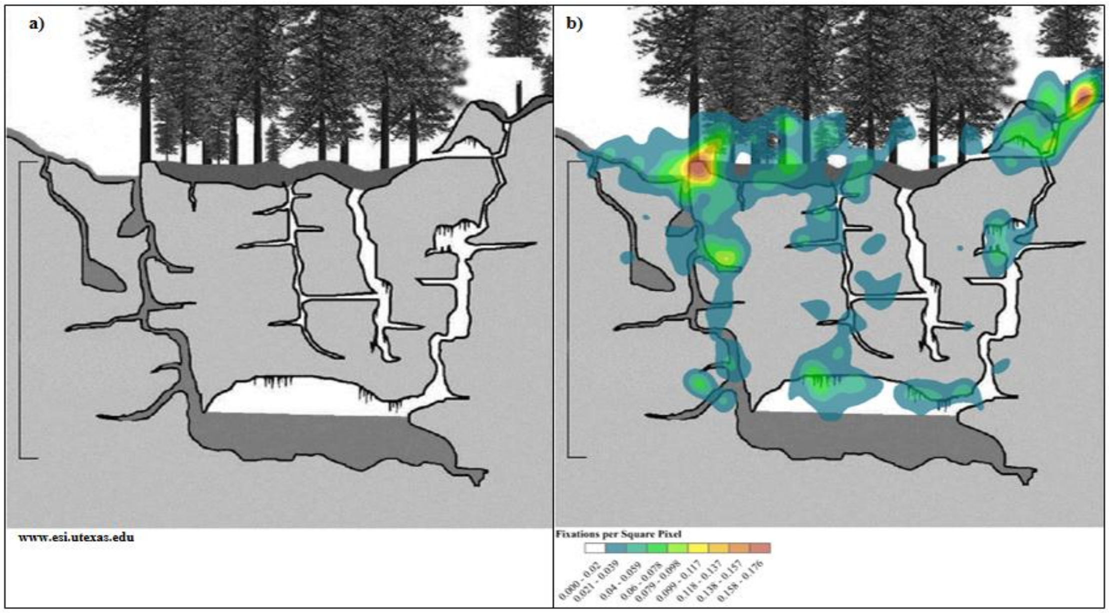


Figure 4.9. a) Karst visual with no labels without color b) KDE results of NGPT5

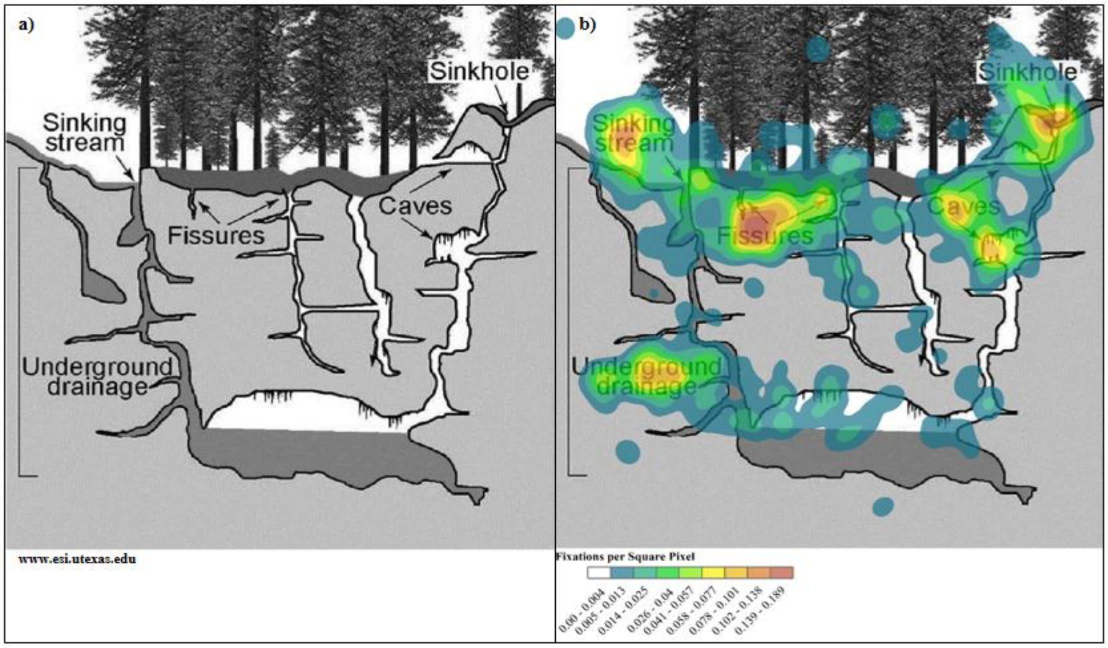


Figure 4.10. a) Karst visual with labels without color b) KDE results of NGPT6

The pre- and post-assessments, semi-structured interviews, and quantitative eye-tracking KDE analysis reveal that both sets of visualizations were helpful to participants without prior geoscience knowledge to define a karst landscape and understand human impacts to karst areas. After viewing either the visualization without labels or color or the visualization with labels but without color, the participants showed better learning outcomes when defining a karst landscape on PostQ1, identifying the major human impacts on karst groundwater on PostQ3, and listing the major contaminants of a karst system on PostQ9 (Figures 4.11 and 4.12, Appendix D Tables 5 and 6).

The major differences in learning outcomes when comparing the visualization without labels or color to the visualization with labels but without color, was on PostQ5 and PostQ7. On PostQ5 after viewing the visualization without labels, 40% of participants answered incorrectly and 60% of participants answered partial correctly. Conversely on PostQ5, after viewing the visualization with labels, 20% of participants answered partial correctly and 80% of participants answered correctly. These results suggest that more participants achieved higher learning outcomes after viewing the visualization with labels. Additionally, the participants that viewed the visualization either did not have a response to PostQ5 or his/her response indicated confusions. Examples of their responses to PostQ5 include:

1. “Caves, crystals, not sure really”
2. “There are several tunnels leading to a large area underground”

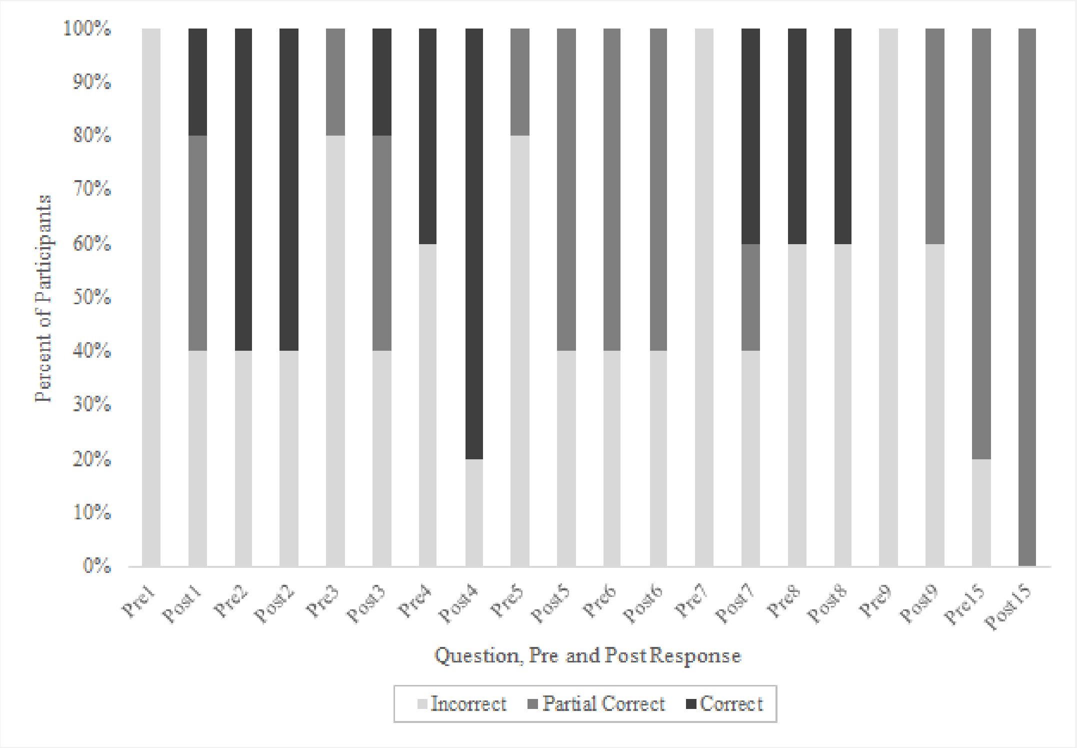


Figure 4.11. Pre- and post-responses of NPGT5 participants.

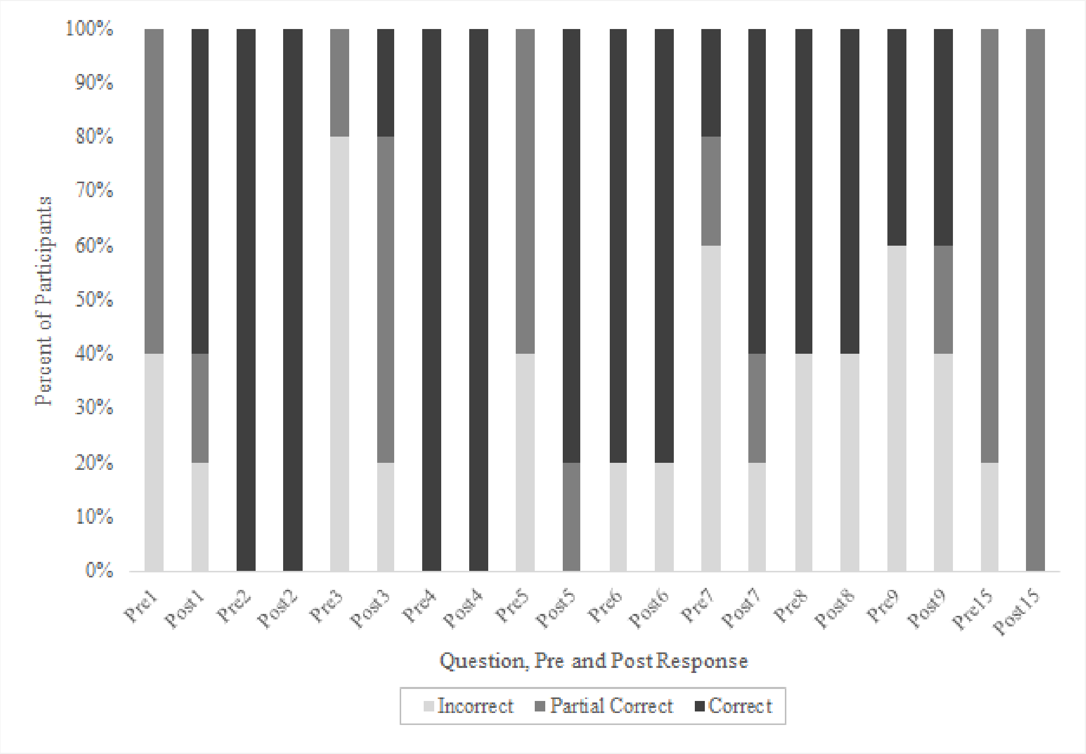


Figure 4.12. Pre- and post-responses of NPGT6 participants.

Out of the total participants that viewed the visualization with labels that were asked to list the features of a karst landscape on PostQ5, 4 out of 5 participants mentioned “sinkholes”, 2 out of 5 participants mentioned “caves,” and 3 out of 5 participants mentioned “fissures.” The visualization included “sinkhole”, “caves”, and “fissures” labels in the visualization, and after viewing the KDE analyses for each visualization, it is evident that the participants who viewed the visualization with labels showed concentrated areas of fixations on each of those labels. Additionally, responses for all participants from each trial revealed that 10 out of 10 participants were able to name the features of a karst landscape based on the labels in the visualization.

On PostQ7, after viewing the visualization without labels, 20% of participants answered partial correctly, and 40% of participants answered correctly, while 20% of participants answered partial correctly and 60% of participants answered correctly to the same question after viewing the visualization with labels. These results indicate that better learning outcomes were achieved on the visualization with labels when participants were asked about the connectivity between the surface and subsurface. The KDE analyses for both visualizations further strengthen these results by showing highly concentrated areas of fixation around the “underground drainage” label and the actual water in the drainage area for the visualization with labels. The KDE analysis for the visualization without labels shows none to very few fixations by participants on the water in the underground drainage area. Furthermore, when asked about improvements that could be made to each of these visualizations, 6 out of 10 participants combined from both trials suggested that color could be added to improve their understanding of a karst landscape. The results of this set of trials further demonstrated the importance of adding labels to a visualization to help non-prior karst geoscience knowledge participants identify the main features of a karst landscape. Participants that first viewed the visualization with no color or labels demonstrated confusion in post-assessment responses when asked to identify main karst features. Additionally, the results of the trial with the visualization without color but with labels not only demonstrated the importance of labels to identify features, but also demonstrated the importance of label placements. For example, in general, when labels were combined with arrows to point to the feature, the fixations of the participants' indicated that the attention of the participants was drawn to the label and the features (i.e. the KDE analysis of the "caves" label and arrows pointing to caves). These findings build upon the study conducted by Botelho and Morias (2006) that suggested the placement and reading of labels and content plays a critical part in the learning of an observer.

However, the results of the trial with the visualization without color but with labels showed the possible distraction that arrows can have on participants' fixations. The largest concentration of fixations of participants that viewed the visualization with labels were around the labels; therefore, the 5 karst visualizations for the large group trials were intentionally developed to have labels written outside of the visualization and then lines pointing to the feature inside the visualization to draw the attention of the observer inside the visualization.

4.1.4 Experiment 4: Color versus No Color without Labels

The KDE results for the participants that viewed the karst visualization without labels and without color and the participants that viewed the karst visualization without labels but with color, that participants show definite regions of interest (ROI) or "hotspots" where the participants spent longer portions of time viewing specific areas of the visualization (Figures 4.13 and 4.14, Appendix C Figures 7 and.8)**.** However, these ROIs varied for each participant group. Participants who viewed the karst visualization without labels or color showed fewer fixations on specific ROIS than participants that viewed the same visualization with labels. Most hotspots or fixations occurred on water entering the cracks and crevices on the left side and middle of the visualization, with hotspots also occurring on the stalactites and water in the drainage basin. Conversely, participants that viewed the karst visualization without labels but with color, show many more ROIs towards the top of the visualization where the water is entering on the left side, the middle crack of the visualization, and on the sinkhole area on the upper right side. Fixations are also present throughout the cracks and crevices of the subsurface and the water in the drainage basin.

Various data reveal that both sets of visualizations were helpful to participants with no prior karst knowledge to identify karst features and list major contaminants. After viewing either the visualization without labels and color or the visualization without labels but with color, more participants were able to partial answer how to define a karst landscape on PostQ1, name the features of a karst landscape on PostQ5, and list major contaminants of a karst system on PostQ9. The major differences in learning outcomes when comparing the visualization without labels and color to the visualization without labels but with color, was on PostQ7, which asked about the connectivity between the surface and subsurface.

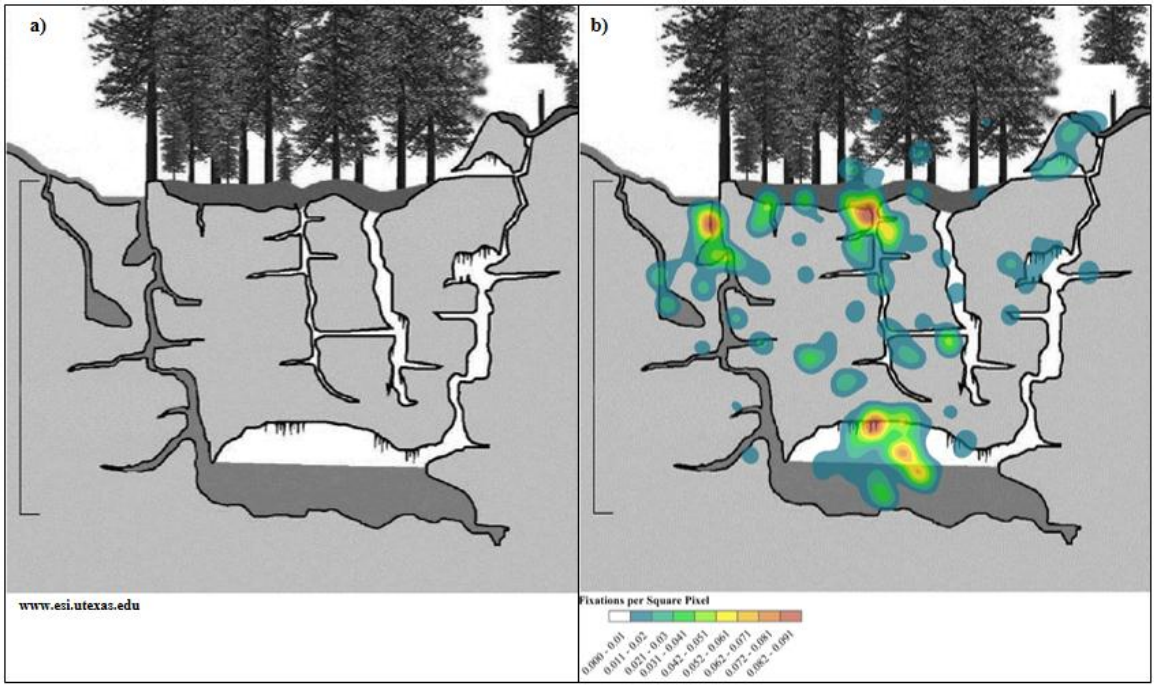


Figure 4.13. a) Karst visual with no labels without color b) KDE results of NGPT7.

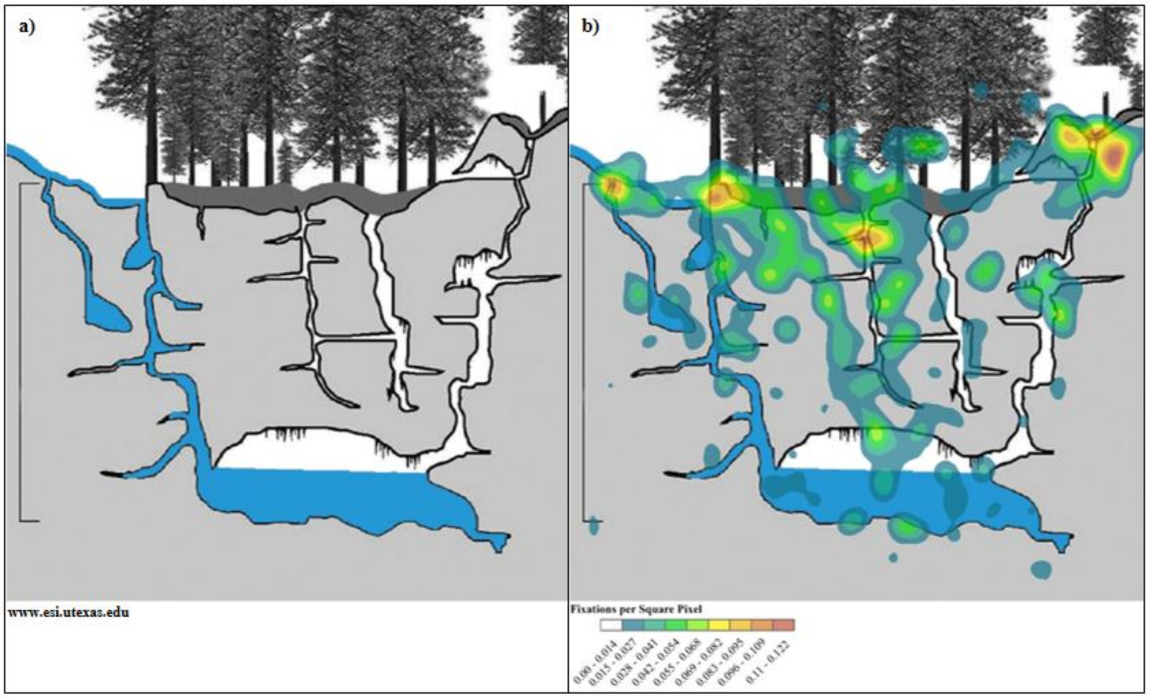


Figure 4.14. a) Karst visual with no labels with color b) KDE results of NGPT8.

On PostQ7, after viewing the visualization without labels and color, 40% of participants answered incorrectly and 60% of participants answered partial correctly. Conversely, after viewing the visualization without labels but with color, 20% of participants answered incorrectly, 20% of participants answered partial correctly, and 60% of participants answered correctly to the same question. These results indicate that higher learning outcomes were achieved with the visualization without labels but with color when participants were asked about the connectivity between the surface and subsurface. The KDE analyses for the visualization with color further strengthen these results by showing more concentrated areas of fixation around the left side of the visualization where the blue-colored water is entering the subsurface. Also, 4 out of 5 participants that viewed the visualization with color listed water as a feature of a karst landscape on PostQ5, while 0 out of 5 participants did not list water as a karst feature for PostQ5. Furthermore, after viewing both visualizations, 8 out of 10 participants indicated during semi-structured interviews that color was helpful to improve their understanding of a karst landscapes (Figures 4.15 and 4.16, Appendix D Tables 7 and 8).

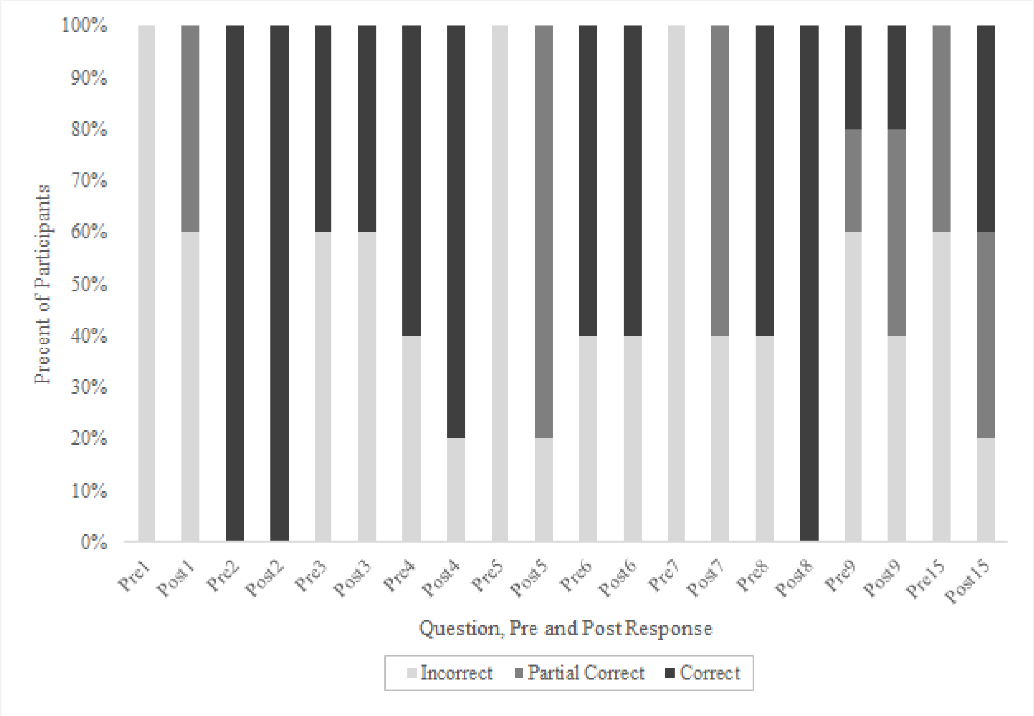


Figure 4.15. Pre- and post-responses of NPGT7 participants.

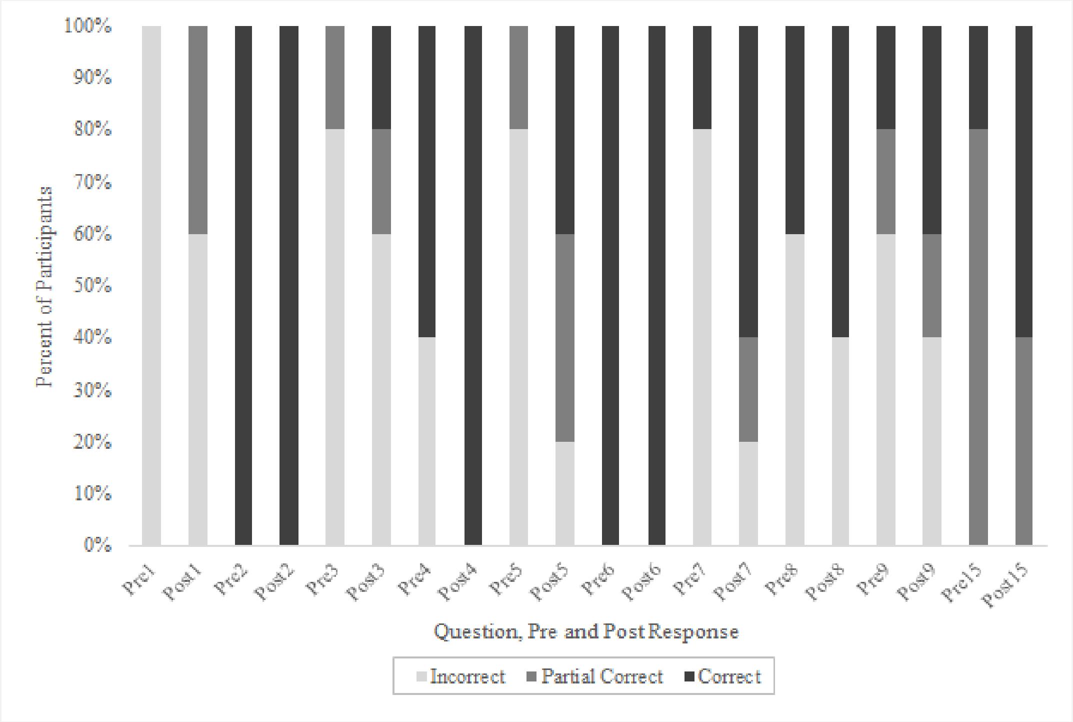


Figure 4.16. Pre- and post-responses of NPGT8 participants.

The results of these trials made a robust argument for the importance of color incorporated into visualizations, especially in the case of karst visualizations. In a karst landscape, the concept of the interconnectedness between the surface and the subsurface is equally important as labels of features for a non-prior karst geoscience knowledge participant to understand. By adding color to the water in this set of visualizations, learning outcomes improved in regards to the understanding of the connectivity between the surface and the subsurface and the notion that water one of the main karst landscape features. These findings build upon the preliminary study of Griffin and Robinson (2010) that found color was an effective way of communicating information that was embedded into a coordinated display. Color was, therefore, incorporated into all 5 karst visualizations developed for the large group trials and the shading of color was designed to be minimalistic and adhere to a brand identity with the same shading and contrast present in all 5 karst visualizations.

4.1.5 Experiment 5: 2D versus 3D, Static Orientation with Labels

The KDE results for the participants that viewed the karst visualization with 2D orientation and labels and for the participants that viewed the karst visualization with 3D, static orientation with labels show definite regions of interest (ROI) or "hotspots" where the participants spent longer portions of time viewing specific areas of the visualization (Figure 4.17 and 4.18, Appendix C Figures 9 and 10)**.** However, these ROIs varied slightly for each participant group. Participants that viewed the karst visualization with 2D orientation with labels, showed the most concentrated fixations on the "acidic rainwater" traveling into the limestone callout, "disappearing stream" label, and "carbon dioxide dissolves into water" label. These participants also had more fixations on the "cracks in limestone”, “volcanic rock”, “limestone”, “cave”, “spring”, and “volcanic and sedimentary rock” labels, as well as fixation points on the waterfall entering the subsurface ROI and throughout the waterfall. Similarly, most hotspots or fixations of participants that viewed the karst visualization with 3D, static orientation with labels were most concentrated on the “acidic rainwater” traveling into the “limestone” callout and “carbon dioxide dissolves into water” label. These participants also had more fixations on the “cracks in limestone”, “disappearing stream”, “volcanic rock”, “limestone”, “cave”, “spring”, and “volcanic and sedimentary rock” labels, as well as less concentrated fixation points on the waterfall entering the subsurface ROI.

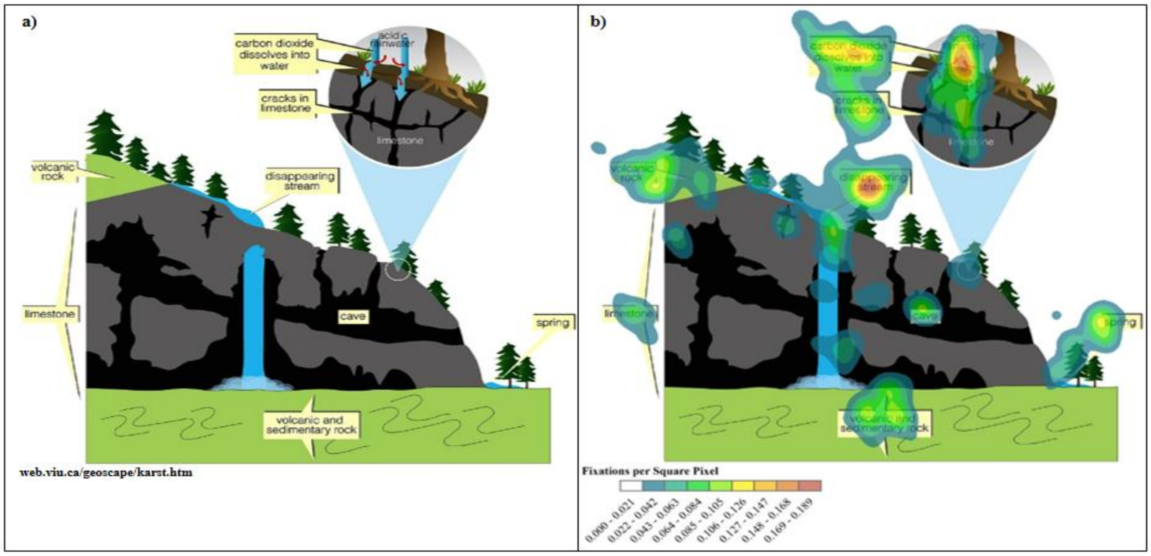


Figure 4.17. a) 2D karst visualization with labels b) KDE results of NGPT9.

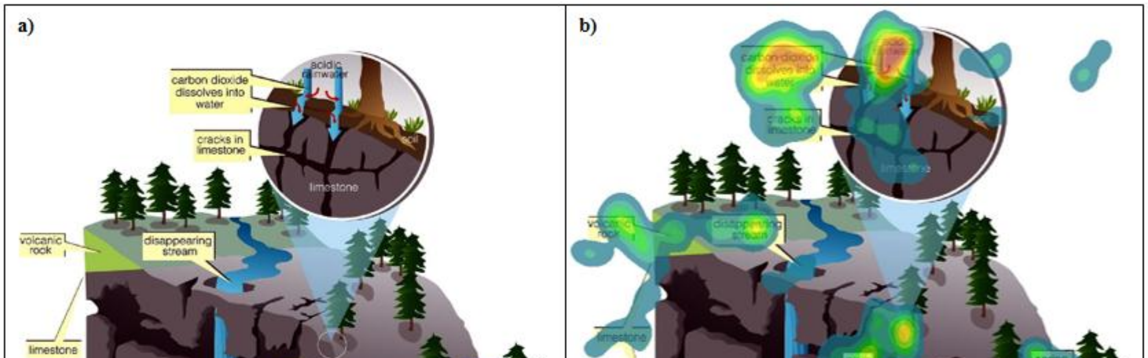


Figure 4.18. a) 3D karst visualization with labels b) KDE results of NGPT10.

Collectively, experiment 5 data reveal that both sets of visualizations were helpful to participants with no prior karst knowledge to define a karst landscape and the connection between the surface and subsurface. After viewing either the 2D visualization with labels and color or the 3D, static visualization with labels and color, more participants were able to answer partial correctly how to define a karst landscape on PostQ1, correctly describe the surface and subsurface connectivity on PostQ7, and indicate the importance of karst water resources on PostQ15 (Figures 4.19 and 4.20, Appendix D, Tables 9 and 10). The major difference in learning outcomes when comparing the visualization in 2D versus 3D statics was on PostQ5 that asked participants to list the main features of a karst.

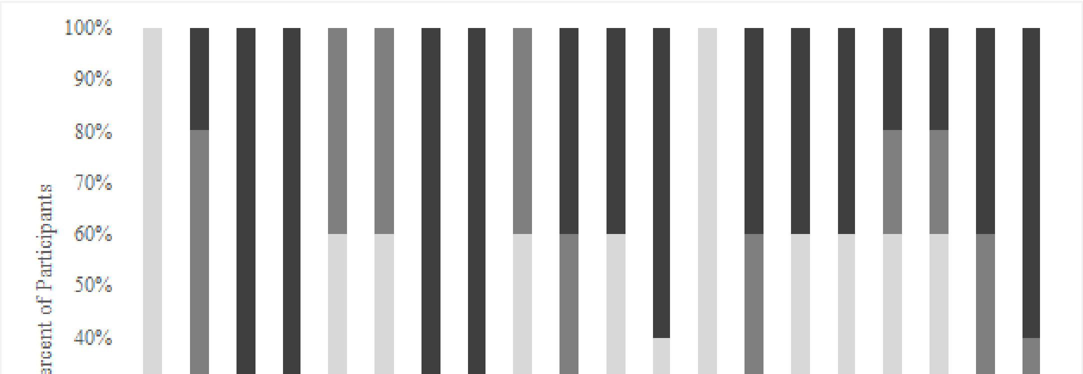


Figure 4.19. Pre- and post-responses of NPGT9 participants.

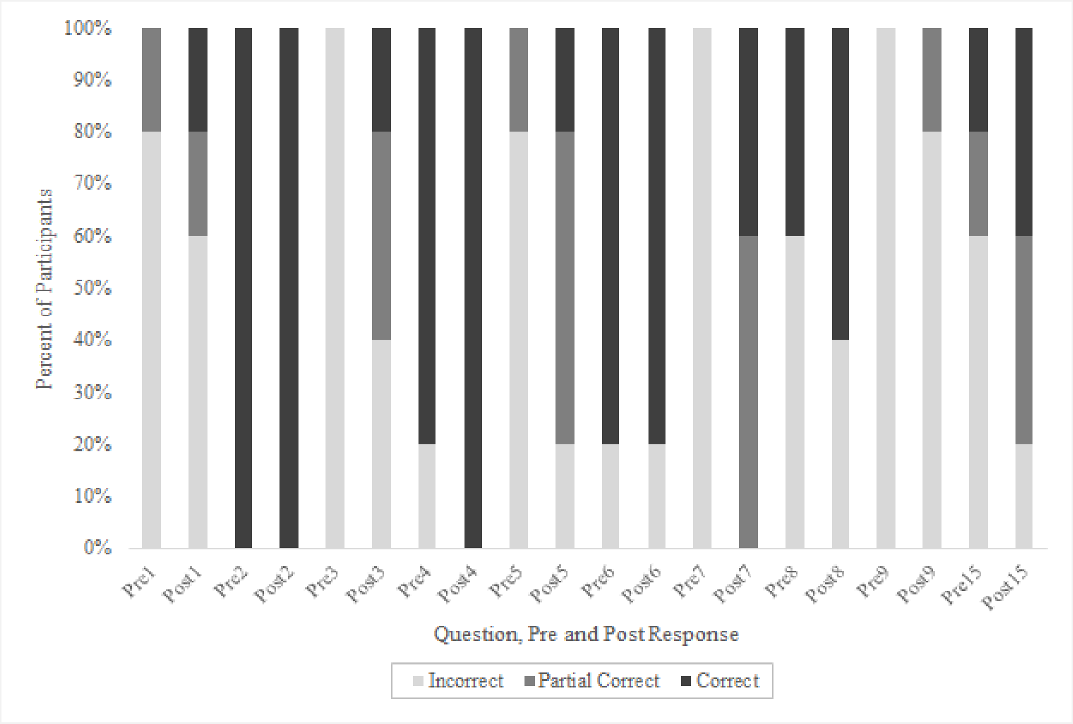


Figure 4.20. Pre- and post-responses of NPGT10 participants.

On PostQ5 after viewing the 2D visualization, 60% of participants answered partial correctly and 40% of participants answered correctly. Conversely, after viewing the 3D visualization, on PostQ5, 20% of participants answered incorrectly, 60% of participants answered partial correctly, and 20% of participants answered correctly. These results indicate that higher learning outcomes were achieved on the 2D visualization when participants were asked to list the main karst landscape features. The KDE analyses for both visualizations show fixations occurred on every label in the visualizations. These fixations on the labels are further verified on the post-assessment for each trial. In response to PostQ5 after viewing the 2D visualization, 2 out of 5 participants listed cracks, 3/5 participants listed caves, and 2 out of 5 participants listed limestone. For the 3D, static visualization 2 out of 5 participants listed cracks, 2 out of 5 participants listed caves, and 3 out of 5 participants listed water or flowing water.

Furthermore, even though more participants were able to correctly list the main features of a karst landscape after viewing the 2D visualization, 7 out of 10 participants from both trials indicated in semi-structured interviews that the 3D, static visualization was more helpful in determining how and where the water was flowing in the visualization. Here are some example responses of participants that preferred the 3D visualization:

1. "I liked the 2nd [3D] visualization because you could see that the stream was running through the cave and out. Couldn't see it coming out of the cave from the 1st [2D] visualization."
2. "The 1st [3D] visualization was better because I was able to follow stream after it left underground cavern."

A larger concentration of fixations on labels in both visualizations was verified further when participants were asked about how humans impact groundwater resources in a karst landscape. Four out of 10 participants indicated "acid rain" as a culprit for contamination caused by humans in a karst landscape. Some example post-assessment responses indicated acid rain as a contaminant included:

1. “[Humans] polluting the air and therefore acid rain affects the purity of caves and water in caves
2. Air pollutants dissolved in the groundwater, garbage and waste entering the groundwater, acid rain, and acidic waters.”

Based on the results of these two trials, two important points should be considered when developing a karst visualization: 1) labels have large influence on participants’ fixation leaving many parts of the visualization unviewed, and 2) visualization developers must ensure accurate concepts are conveyed. For example, participants believed the label “Acidic Rainwater” was demonstrating a contamination source instead of a karst formation process. Therefore, in the large group trials the label “Acidic Rainwater” was replaced with “Rainwater” and labels were placed outside of the visualization to have participants’ attention focus inside the visualization.

In terms of the influence of labels on participant’s fixations, this discovery could potentially explain the greater learning outcomes achieved by participants when viewing the 2D visualization with labels versus the 3D visualization with labels. Therefore, the final small group experiment (SGE6) was conducted to explore the educational effectiveness of 2D versus 3D orientation without labels.

4.1.6 Experiment 6: 2D versus 3D, Static Orientation without Labels

The KDE results for the participants that viewed the karst visualization with 2D orientation with labels and for the participants that viewed the karst visualization with 3D, static orientation with labels, show definite regions of interest (ROI) or “hotspots” where the participants spent longer portions of time viewing specific areas of the visualization

(Figures 4.21 and 4.22, Figures 11 and 12)**.** Participants that viewed the karst visualization with 2D orientation but without labels, showed the most concentrated fixations or hotspots on the waterfall entrance into the subsurface as well as less dense fixations at the end of the waterfall and spring exiting on the right. Conversely, most hotspots or fixations of participants that viewed the karst visualization with 3D, static orientation without labels were concentrated on the entire surface steam, subsurface waterfall, and output spring. Less concentrated fixations occurred on surface cracks and crevices leading to the subsurface and subsurface conduits.

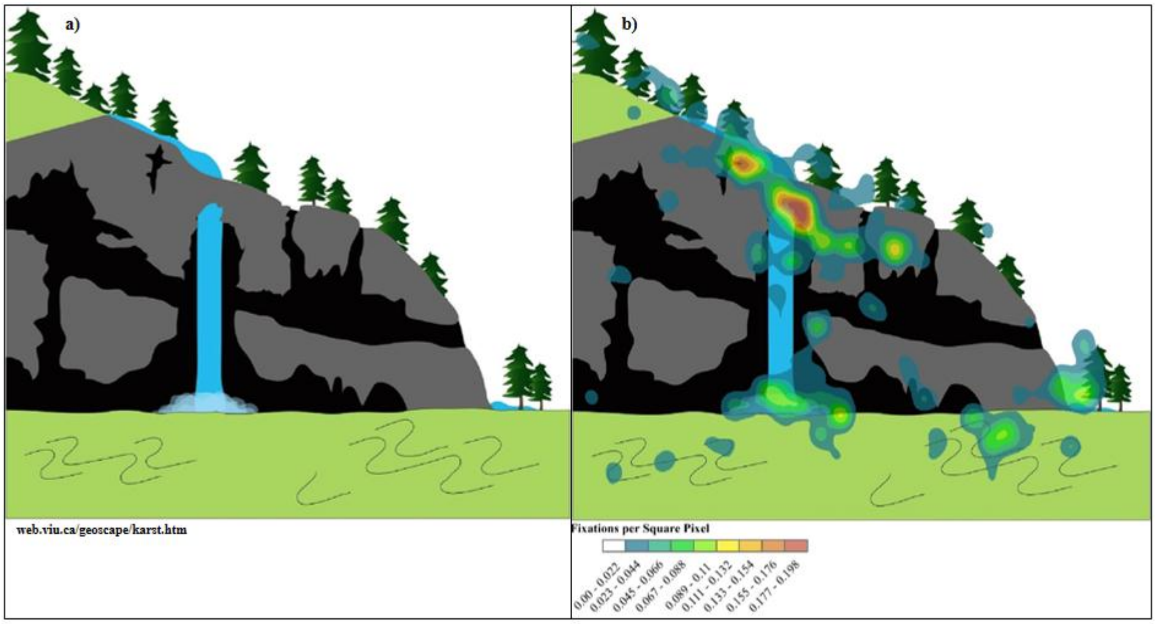


Figure 4.21. a) 2D karst visualization without labels b) KDE results of NGPT11.

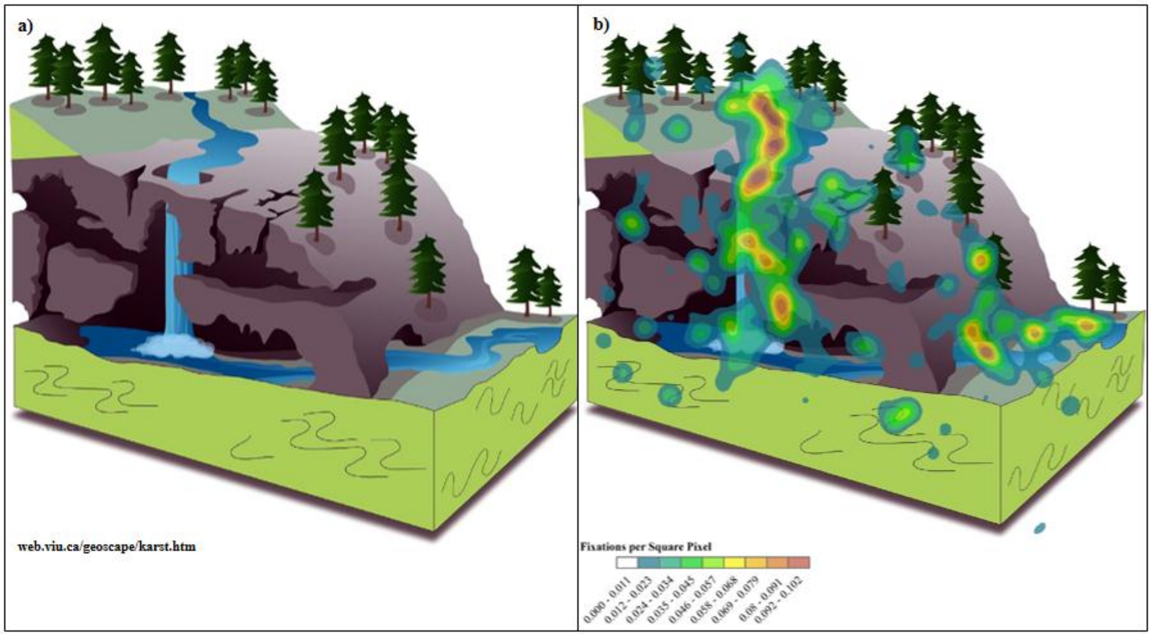


Figure 4.22. a) 3D karst visualization without labels b) KDE results of NGPT12.

The pre- and post-assessments, semi-structured interview data, and quantitative eye-tracking KDE analysis reveal that both sets of visualizations were helpful to participants without prior karst knowledge to name the main features of a karst landscape and understand the connectivity between the surface and subsurface. After viewing either the 2D visualization without labels and with color or the 3D, static visualization without labels but with color, very similar learning outcomes were achieved. For trial NPGT11, more participants answered partial correctly how to define a karst landscape on PostQ1, answered partial correctly when asked to identify karst landscape features, correctly described the surface and subsurface connectivity in response to PostQ7, and indicated the importance of karst water resources on PostQ15 (Figures 4.23 and 4.24, Appendix D Tables 11 and 12).

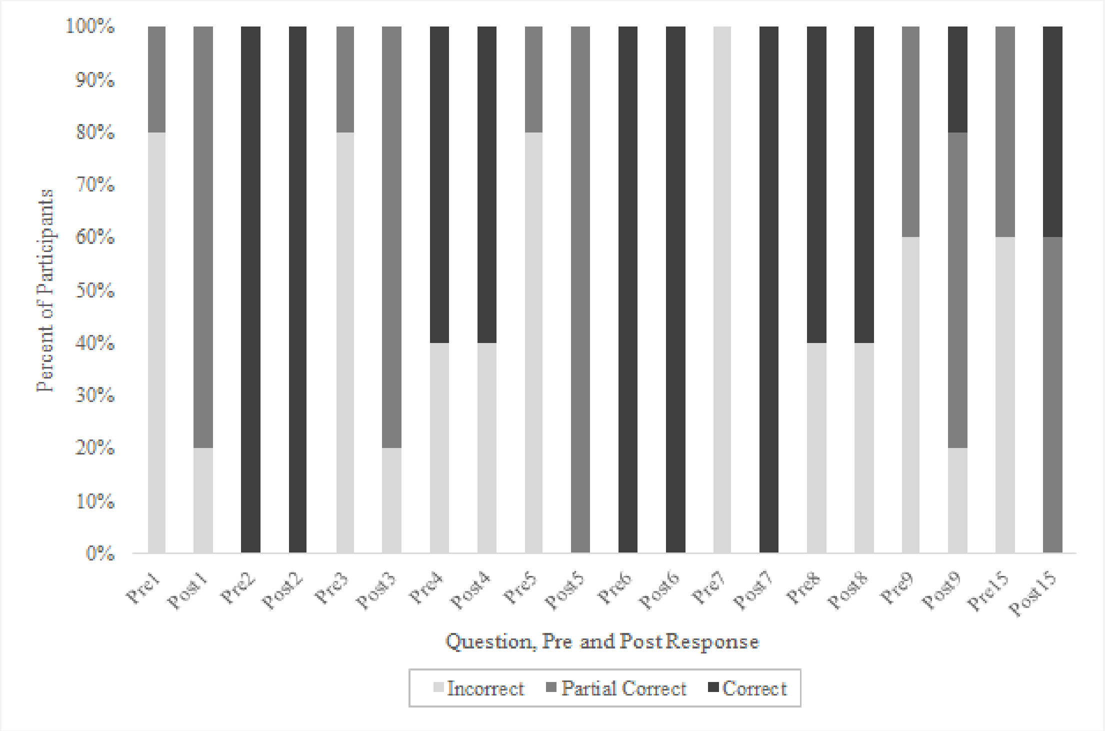


Figure 4.23. Pre- and post-responses of NPGT11 participants.

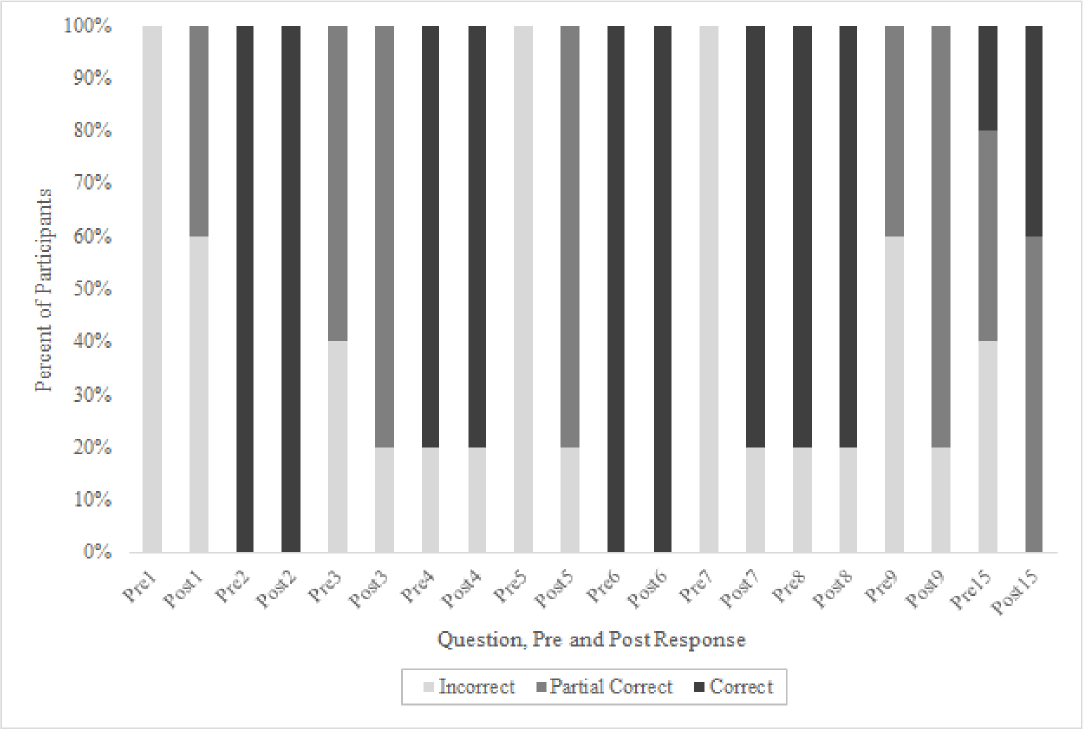


Figure 4.24. Pre- and post-responses of NPGT12 participants.

The major differences on post-assessment responses of participants occurred on PostQ5 when asked to list the main features of a karst landscape. After viewing the 2D visualization without labels, 4 out of 5 participants indicated hills or high elevation and 3 out of 5 participants indicated water. After viewing the 3D visualization without labels, 2 out of 5 participants indicated underground rivers or water and 3 out of 5 participants indicated flowing or moving water. The participants' responses after viewing the 3D visualization without labels are in accordance with the KDE analysis for that visualization which shows that the most concentrated fixations occurred on the entire surface steam, subsurface waterfall, and output spring. Furthermore, 8 out of 10 participants from both trials indicated that the 3D visualization without labels was more helpful in explaining where the water was located and flowing in the visualization. Here are some example responses of participants that preferred the 3D visualization:

1. “The 1st [3D] one [was more helpful] because I could see exactly where it was going the whole time. There was no break where you had to assume where the water was going.”
2. “The second one because I could see more of it [the karst landscape] and where the water was actually going”

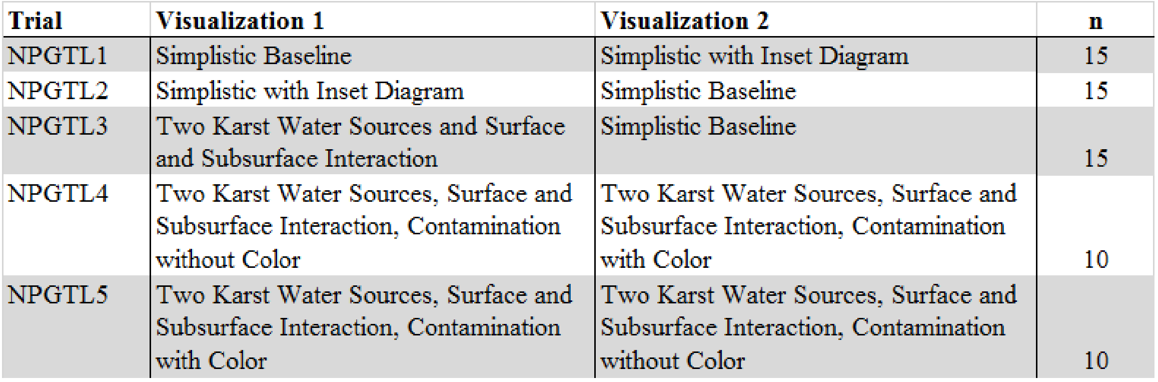
The findings from this small group experiment help bridge the gap presented by Reynolds et al. (2005) between non-prior geoscience students’ understanding of geological concepts in 2D and 3D oriented visualizations. The results from these two trials indicate the need for a 3D, static karst visualization to fully convey the connectivity of water between the surface and subsurface of a karst landscape to non-prior karst geoscience participants. Therefore, all of the 5 visualizations in the large group trials were developed in a 3D, static orientation.

4.2 Large Group Trials

Each large group trial tested a new karst visualization, and was setup to have a more robust sample size. For the first three new karst visualization trials there were 15 participants per trial, and for the last two new karst visualization trials, which focused on human karst contamination, there were 10 participants per trial (Table 4.2). A total of 65 participants were in the large group trials. An example of the trial structure for the large group trial is as follows: the participant took a pre-assessment, viewed 1 of the 5 new karst visualization, took a post-assessment, viewed a different new karst visualization, and participated in a semi-structured interview. Refer to Table 3.2 for an overview of the pre-and post-assessment questions that were analyzed using the percent change of learning outcomes for large group participants.

The results of these trials provided new insight into the development process that needs to occur in order to produce an effective karst visualization, and they helped identify the most effective karst visualizations of the new karst visualizations.

Table 4.2 Summary of large group trials.



Trial	**Visualization 1**	**Visualization 2**	**n**
NPGTL1	Simplistic Baseline	Simplistic with Inset Diagram	15
NPGTL2	Simplistic with Inset Diagram	Simplistic Baseline	15
NPGTL3	Two Karst Water Sources and Surface and Subsurface Interaction	Simplistic Baseline	15
NPGTL4	Two Karst Water Sources, Surface and Subsurface Interaction, Contamination without Color	Two Karst Water Sources, Surface and Subsurface Interaction, Contamination with Color	10
NPGTL5	Two Karst Water Sources, Surface and Subsurface Interaction, Contamination with Color	Two Karst Water Sources, Surface and Subsurface Interaction, Contamination without Color	10

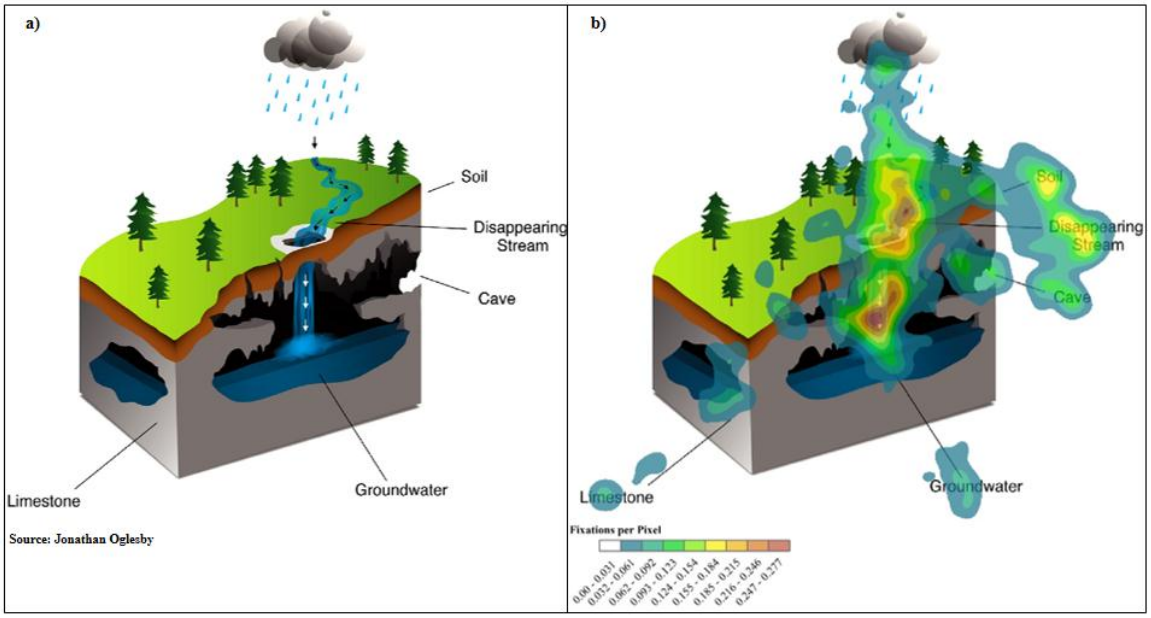
4.2.1 3D, Static Simplistic Baseline

In this karst visualization, the combined most effective visual stimuli from the small group experiments present in this visualization were labels displayed outside of the visualization, 3D, static orientation, the incorporation of color, and arrows demonstrating the directionality of the rainwater going into the disappearing stream and then under the surface to the subsurface groundwater. For this first new karst visualization, the goal was to make it as simplistic as possible to serve as a baseline for the other 4 large group karst visualization trials.

The KDE results for the participants that viewed the karst visualization, show definite regions of interest (ROI) or “hotspots” where the participants spent longer portions of time viewing specific areas of the visualization (Figure 4.25, Appendix C Figure 13)**.**

Most hotspots or fixations of participants that viewed the karst visualization were concentrated on the entire surface steam and subsurface waterfall falling into the groundwater with directional movement shown by arrows, the cloud and rain falling into the disappearing stream indicated by the arrow, the "soil", "disappearing stream" and "cave" labels, and the conduit that the "cave" label is pointing to in the visualization. Less concentrated areas of fixation include the "groundwater" label, "limestone" label, and the area it is pointing to in the visualization.

Overall, the pre- and post-assessments, semi-structured interviews, and quantitative eye-tracking KDE analysis reveal this visualization was helpful to participants with no prior karst knowledge to understand the surface and subsurface connectivity. The most notable differences in learning outcomes between the pre- and post-assessments occurred on PostQ5 with 80% of participants correctly answering why karst landscapes lack surface water, PostQ6 with 46.67% of participants partial correctly and 26.67% of participants identifying karst features, PostQ7 with 40% of participants answering partial correctly and 33.33% of participants answering correctly the primary cause of karst or cave formation, and PostQ8 with 33.33% of participants answering partial correctly and 26.67% of participants answering correctly the connection between the surface and subsurface in a karst landscape ((Figure 4.26, Appendix D Table 13).



Source: Jonathan Oglesby

Figure 4.25 a) 1st new karst visualization b) KDE results of NPGL1.

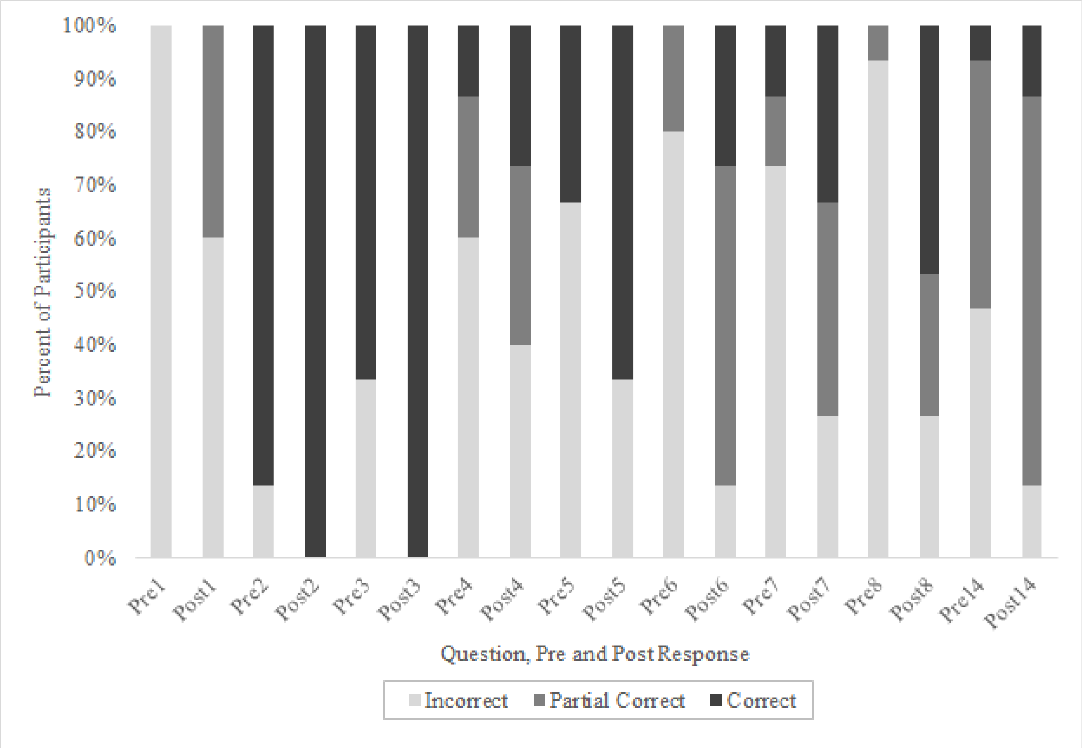


Figure 4.26. Pre- and post-responses of NPGTL1 participants.

A Wilcoxon signed-rank sum, two-tailed test was performed on the PreQ6 and PostQ6 and showed statistically significant differences between participants' responses for PreQ6 and PostQ6 ($p < 0.001$). The Wilcoxon analysis was performed to validate the sample size of this large group trial. As aforementioned in the methodology, Pre/PostQ6 were selected for the analysis through random number selection of all question numbers. Only one question was randomly selected because prior Wilcoxon analyses were performed on multiple pre- and post-assessments from a chosen large group trial and the statistically significant results were similar for all pre- and post-questions.

From the KDE analysis, it is evident that some of the highest concentration of fixations occurred around the labels and this was further strengthened by participants' responses to PostQ6 that asked them to identify main karst features. On PostQ6, 8 out of 15 participants identified limestone, 8 out of 15 participant identified caves, 7 out of 15 participants identified groundwater, 6 out of 15 participants identified soil, 6 out of 15 participants identified rain or rainfall, and 3 out of 15 indicated a disappearing water source (i.e. stream or river).

Even though, this visualization showed an increase in learning outcomes for participants in terms of the key features of a karst landscape and the surface and subsurface connectivity, participants were lacking responses that showed an understanding of the different ways water can travel through the surface to the subsurface in karst areas. On PostQ8 when asked about surface and subsurface connectivity of a karst landscape, many participants were vague in their responses, mainly describing that the connectivity is made by water, rock, soil, and streams. However, a key concept in the understanding of a karst landscape is to understand the importance of rainfall traveling through the surface to reach the limestone which helps explain how caves can rapidly form and how storm water can contaminate karst aquifers.

Generally, the results of this first trial suggested that this visualization was educationally effective in terms of conveying karst features to participants and getting observers to understand the connectivity of the surface and subsurface in a karst landscape. However, participants showed evidence of not receiving a complete understanding of key elements of a karst landscape that are critical to communicate to non-karst experts, especially in terms of their understanding of karst concepts such as storm water contamination.

4.2.2 3D, Static Simplistic Karst Visualization with Surface/Subsurface Inset Diagram

For this second new karst visualization, the combined most effective visual stimuli from the small group experiments present were labels displayed outside of the visualization, 3D, static orientation, the incorporation of color, arrows demonstrating the directionality of the rainwater going into the disappearing stream and then under the surface to the subsurface groundwater, and an inset picture adapted from the small group trial karst visualization with 3D, static orientation. Labels in the inset showed rainwater seeping into the limestone cracks and crevices of the subsurface. The inset picture was added to this karst visualization to show a zoomed in depiction of one of the most important karst formation processes and on the other part of the visualization the disappearing stream serving as a source of groundwater.

The KDE results for the participants that viewed the karst visualization, show definite regions of interest (ROI) or “hotspots” where the participants spent longer portions of time viewing specific areas of the visualization (Figure 4.27, Appendix C Figure 14). The highest concentration of hotspots or fixations of participants that viewed the karst visualization focused on the inset picture and specifically on the “rain water” label. Other, less concentrated fixations occurred on the sinkhole area where the disappearing stream entered the subsurface, the conduit where the “cave” label points to in the visualization, the arrows that shows the rainwater entering the disappearing stream, the “surface & subsurface interaction”, “soil”, and “disappearing Stream” labels outside of the inset picture, and the “soil” and “limestone” labels inside of the inset picture. Other fixations occurred on the “limestone” and “groundwater” labels outside of the visualization.

Overall, the collected data reveal this visualization was helpful to participants with no prior karst knowledge to understand the connection between the surface and subsurface. The most notable differences in learning outcomes between the pre- and post-assessments occurred on PostQ5 with 66.67% of participants answering correctly why karst landscapes

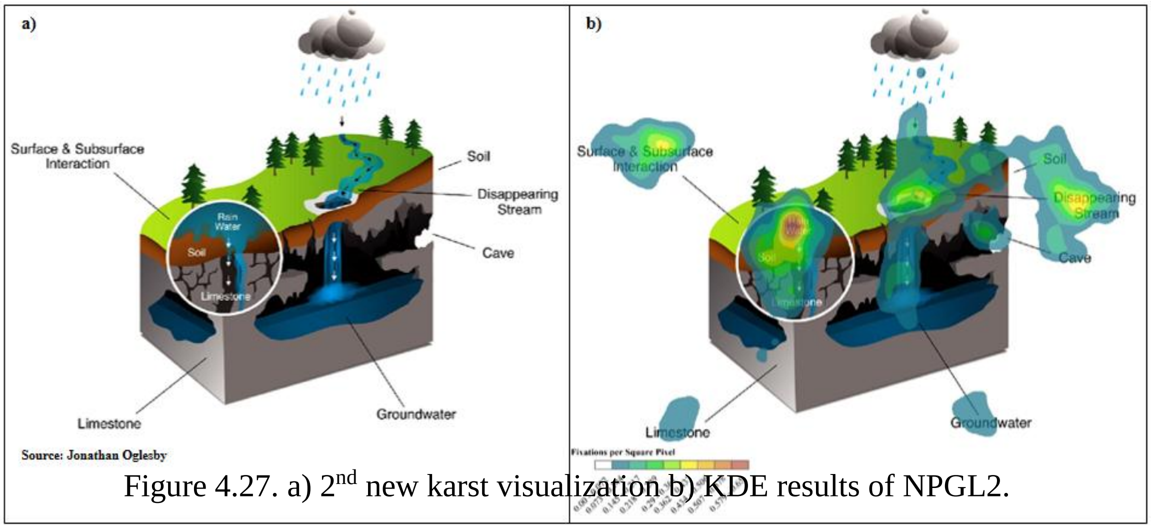


Figure 4.27. a) 2nd new karst visualization b) KDE results of NPGL2.

lack surface water, PostQ6 with 60% of participants partial correctly and 26.67% of participants identifying karst features, PostQ7 with 40% of participants answering partial correctly and 33.33% of participants answering correctly the primary cause of karst or cave formation, and PostQ8 with 26.67% of participants answering partial correctly and 46.67% of participants answering correctly the connection between the surface and subsurface in a karst landscape (Figure 4.28, Appendix D Table 14). A Wilcoxon signed-rank sum, two-tailed test was performed on the PreQ6 and PostQ6 and showed statistically significant differences between participants' responses for PreQ6 and PostQ6 ($p < 0.012$).

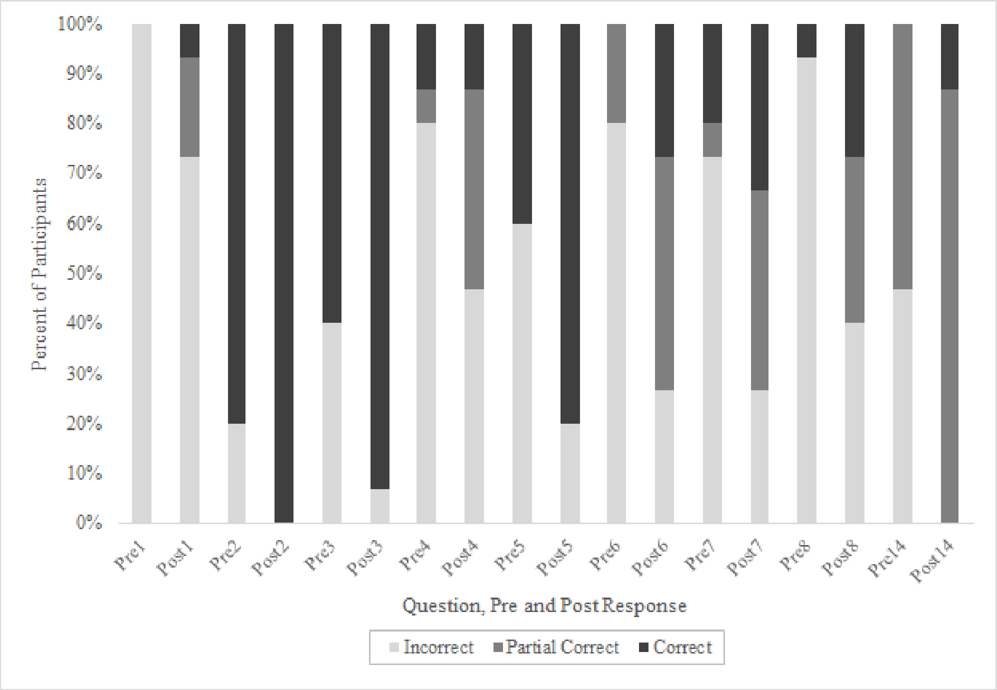


Figure 4.28. Pre- and post-responses of NPGTL2 participants.

From the KDE analysis, it is evident that some of the highest concentration of fixations occurred around the labels, and this was further strengthened by participants' responses to PostQ6 that asked them to identify main karst features. On PostQ6, 9 out of 15 participants identified limestone, 4 out of 15 participant identified caves, 4 out of 15 participants identified groundwater, 5 out of 15 participants identified soil, and 6 out of 15 participants identified rain or rainfall.

The overall results of this visualization indicated that the inset picture was more distracting to non-karst experts than helpful because no notable improvements in learning outcomes were achieved using this visualization as opposed to the first, large group visualization without the inset picture. In fact, more participants that did not view the inset picture in the first visualization, answered partial correctly and correctly how the surface and subsurface were connected in a karst landscape. However, more participants in trial NPG1 that viewed the simplistic visualization first and the visualization with the inset picture second indicated during their semi-structured interviews that the inset picture was more helpful in determining the surface and subsurface interaction in a karst landscape. Their responses included:

1. “The second one had an interaction with the subsurface and top surface interaction. The inset picture caught my eye when I first saw it on the computer

screen. Showing how water had channels going into the underground water and how the soil and limestone met at the top surface."

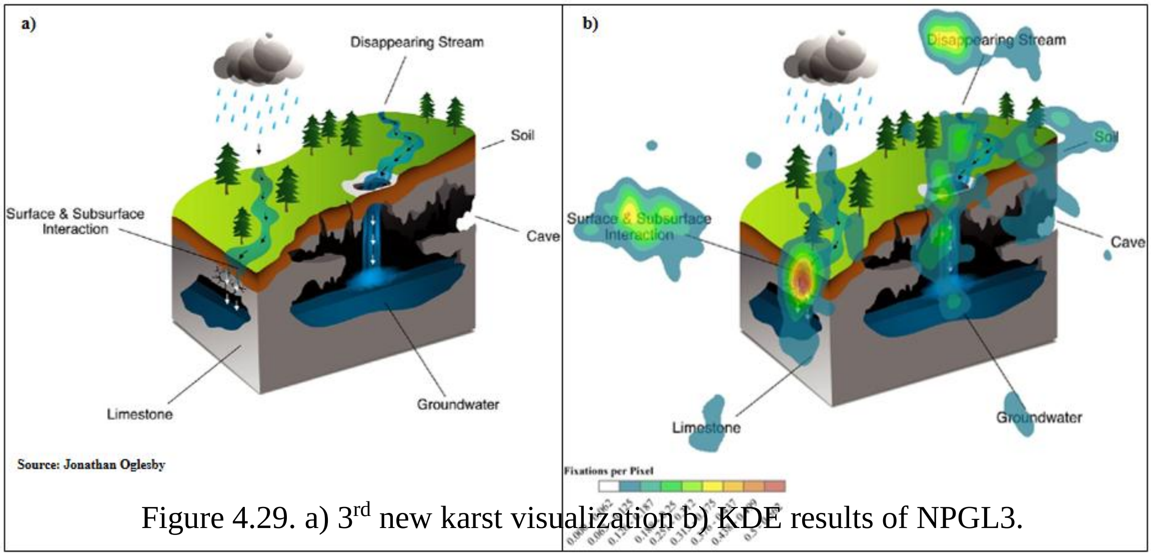
2. "The second one was more detailed had more information I know it had the connection between the surface and subsurface. Inset picture showed the water on top of the soil in the middle with the limestone below and how the water was dripping below into the cave conduit."
3. "The second one actually showed rain and where it went under. It had more information on the second one."

This trial indicated very little improved learning outcomes for participants that first viewed the visualization with the inset picture; however, the conclusions of this trial may not be straightforward based on the semi-structured interviews from NPGT1. The first example response to the semi-structured interview is interesting, especially when the participant noted that the "inset picture caught my eye", and can be used a supporting evidence to the KDE results that shows a large hotspot of fixation in the inset picture. Thus, the inset picture may have been too distracting, but the surface and subsurface interaction concepts of it seemed helpful to participants in NPG1. Therefore, these results allowed for the development of the next karst visualization that incorporated the concepts of the inset picture into the actual karst landscape with the goal of incorporating it without distracting participants.

4.2.3 3D, Static Karst with Surface/ Subsurface Connectivity

For this third new karst visualization, the combined most effective visual stimuli from the small group experiments present were labels displayed outside of the visualization, 3D, static orientation, the incorporation of color, arrows demonstrating the directionality of the disappearing stream, and the incorporation of an inset adapted from the small group experiments that showed rainwater as a separate source for karst water resources seeping into the limestone cracks and crevices of the subsurface.

The KDE results for the participants that viewed the karst visualization, show definite regions of interest (ROI) or “hotspots” where the participants spent longer portions of time viewing specific areas of the visualization (Figure 4.29, Appendix C Figure 15). The highest concentration of hotspots or fixations of participants that viewed the karst visualization focused where the “surface & subsurface interaction” label was pointing to inside the visualization which were the cracks and crevices that had rainwater seeping into them. Other, less concentrated fixations occurred on the entire surface steam and subsurface waterfall falling into the groundwater and the “surface & subsurface interaction”, “soil”, and “disappearing stream” labels around the visualization. Additionally, minor fixations occurred on a small area of rain leading to an arrow and the rainwater stream, the conduit where the “cave” label points into the visualization, and the “groundwater” and “limestone” labels.



Source: Jonathan Oglesby

Figure 4.29. a) 3rd new karst visualization b) KDE results of NPGL3.

The pre- and post-assessments, semi-structured interviews, and quantitative eye-tracking KDE analysis reveal this visualization was helpful to participants without prior karst knowledge to identify karst features and the connection between the surface and subsurface. The most notable differences in learning outcomes between the pre- and post-assessments occurred on PostQ1 with 46.67% of participants answering partial correctly and 13.33% of participants answering correctly how to define a karst landscape, on PostQ5 with 66.67% of participants answering correctly why karst landscapes lack surface water, PostQ6 with 53.33% of participants correctly identifying karst features, PostQ7 with 40% of participants answering partial correctly and 26.67% of participants answering correctly the primary cause of karst or cave formation, and PostQ8 with 20% of participants answering partial correctly and 60% of participants answering correctly the connection between the surface and subsurface in a karst landscape (Figure 4.30, Appendix D Table 15).

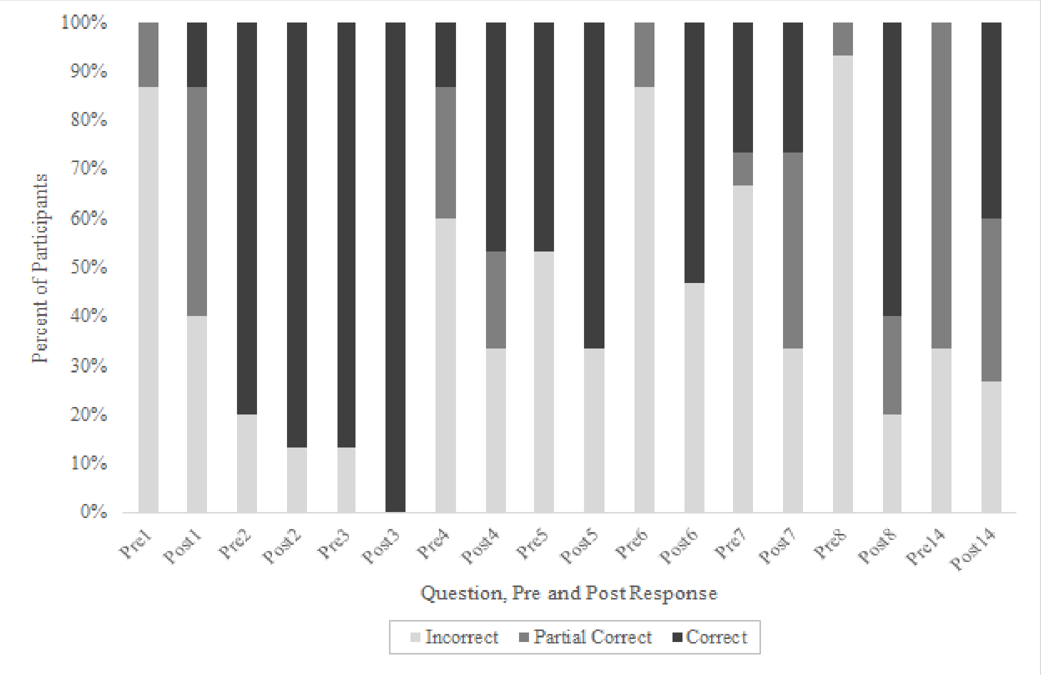


Figure 4.30. Pre- and post-responses of NPGTL3 participants.

From the KDE analysis, it is evident that some of the highest concentration of fixations occurred around the labels and this was further strengthened by participants' responses to PostQ6 that asked them to identify main karst features. On PostQ6, 7 out of 15 participants identified limestone, 13 out of 15 participant identified caves, 10 out of 15 participants identified groundwater, 4 out of 15 participants identified soil, 6 out of 15 participants identified rain or rainfall, 5 out of 15 participants identified a stream or disappearing stream, and 2 out of 15 participants mentioned surface/subsurface interaction. In response to PostQ7, 3 out of 15 participants mentioned water seeping from the surface to the subsurface when asked about the connectivity between the surface and subsurface in a karst landscape. A Wilcoxon signed-rank sum, two-tailed test was performed on the PreQ6 and PostQ6 and showed statistically significant differences between participants' responses for PreQ6 and PostQ6 ($p< 0.0005$), which helps validate the aforementioned conclusions.

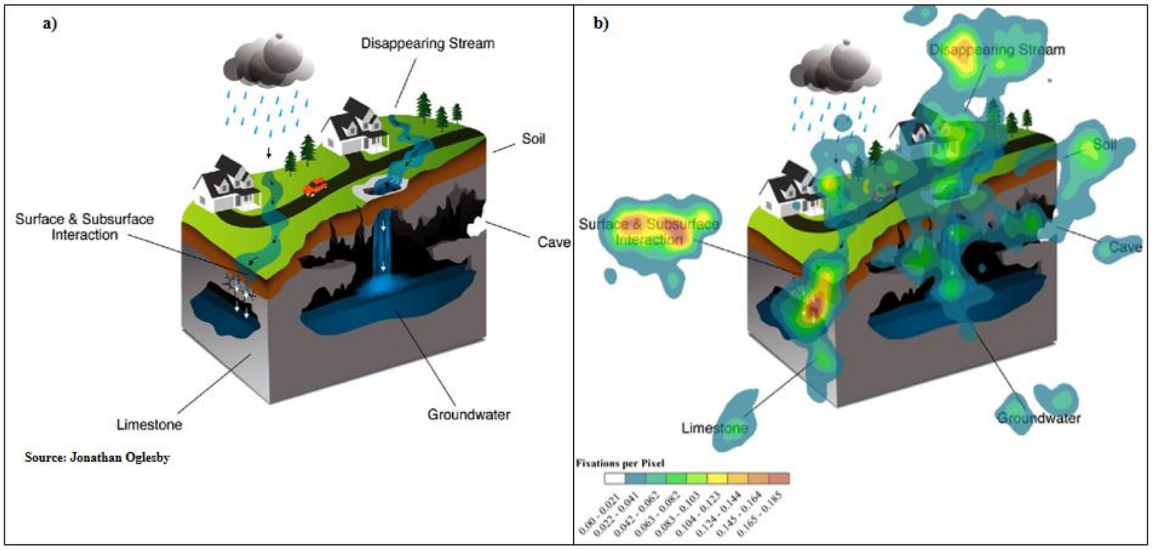
The results of this third large group trial suggest that this visualization was educationally effective especially in terms of conveying the main karst features to participants and getting them to understand the connectivity of the surface and subsurface in a karst landscape. In fact, more participants answered partial correctly and correctly how the surface and subsurface were connected in a karst landscape than participants who viewed the visualizations evaluated in the first and second large group trials. Additionally, participants in this trial not only wrote down a disappearing stream or stream as a main feature of a karst landscape, but some participants also identified rainwater seeping from the surface to the subsurface as a feature of a karst landscape and example of connectivity between the surface and subsurface.

Based on these results, this visualization successfully incorporated the inset picture and achieved higher learning outcomes of participants allowing non karst expert participants to understand the two main sources of water in a karst landscape can come from rainwater seeping into cracks and crevices and disappearing surface streams. The next challenge and visualization concept was to try to convey to participants all of these karst landscape concepts and contamination sources to help them understand their impacts on karst environments.

4.2.4 3D, Static with Surface/Subsurface and Contamination Source

For the fourth new karst visualization, the combined most effective visual stimuli from the small group experiments present were labels displayed outside of the visualization, 3D, static orientation, the incorporation of color, arrows demonstrating the directionality of the disappearing stream, and the incorporation of an inset adapted from the small group experiments that showed rainwater as a separate source for karst water resources seeping into the limestone cracks and crevices of the subsurface. Additionally, new visual stimuli were added to both large group visualization 4 and 5 in the form of a neighborhood with two houses, a road network, and a car. Instead of only conveying the main features of a karst landscape and the connectivity between the surface and subsurface of a karst landscape, the next two visualizations were developed to try to achieve a third learning goal in the form of conveying how karst landscapes are contaminated by residential areas.

The KDE results for the participants that viewed the karst visualization show regions of interest (ROI) or “hotspots” where the participants spent longer portions of time viewing specific areas of the visualization (Figure 4.31, Appendix C Figure 16)**.** The highest concentration of hotspots or fixations of participants that viewed the karst visualization focused specifically on the “surface & subsurface interaction” label, “disappearing stream” label, and the cracks and crevices that had rainwater seeping that is pointed out by the line coming from the “surface and subsurface interaction” label. Other, less concentrated fixations occurred on the right house, the sinkhole area where the disappearing stream entered the subsurface, the start of the rainwater stream to the left, the car, the area surrounding the arrows of the waterfall coming down into the subsurface, conduits on the right side of the visualization, and the “soil”, “cave” groundwater”, and “limestone” labels outside of the visualization.



Source: Jonathan Oglesby

Figure 4.31. a) 4th new karst visualization b) KDE results of NPGL4.

The pre-and post-assessments, semi-structured interview data, and quantitative eye-tracking KDE analysis reveal this visualization was helpful to participants without prior karst knowledge to understand major contaminants of a karst landscape. The most notable differences in learning outcomes between the pre- and post-assessments occurred on PostQ1 with 30% of participants answering partial correctly and 10% of participants answering correctly how to define a karst landscape, on PostQ5 with 60% of participants answering correctly why karst landscapes lack surface water, PostQ6 with 50% of participants partial correctly and 30% of participants correctly identifying karst features, and PostQ8 with 40% of participants answering partial correctly and 30% of participants answering correctly the connection between the surface and subsurface in a karst landscape (Figure 4.32, Appendix D Table 16). A Wilcoxon signed-rank sum, two-tailed test was performed on the PreQ6 and PostQ6 and showed statistically significant differences between participants' responses for PreQ6 and PostQ6 ($p < 0.018$).

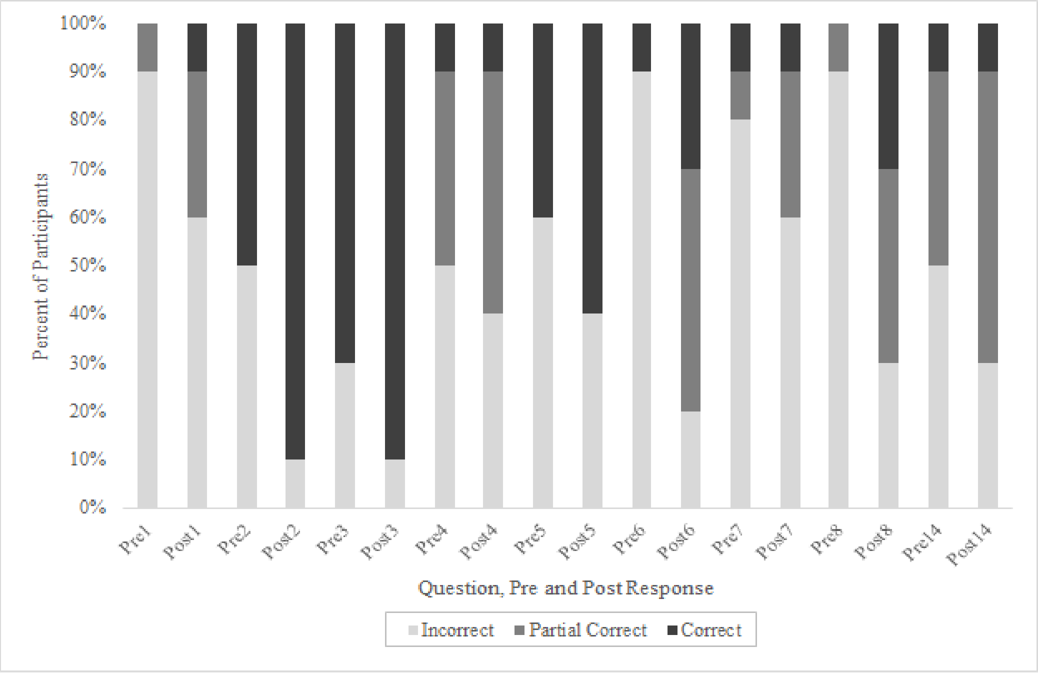


Figure 4.32. Pre- and post-responses of NPGTL4 participants.

From the KDE analysis, it is evident that some of the highest concentration of fixations occurred around the labels and this was further strengthened by participants' responses to PostQ6, which asked them to identify main karst features. On PostQ6, 4 out of 10 participants identified limestone, 5 out of 10 participant identified caves, 3 out of 10 participants identified groundwater, 4 out of 10 participants identified soil, 2 out of 10 participants identified rain or rainfall, 1 out of 10 participants identified a stream and 2 out of 10 participants mentioned surface and subsurface.

Results from this visualization suggest that it did not result in notable differences in pre- and post-assessment learning outcomes in reference to karst contamination from participants on PostQ4, which could result from the lack of color in the stormwater that was present. In fact, when participants were shown a visualization that colored contamination, eight out of the 10 participants did not notice the addition of color and two out of 10 participants suggested in the semi-structured interviews that contaminants be labeled. From this visualization, results suggested that conveying karst contaminants in a residential area cannot be subtle and color or labels must explicitly identify contaminants. This information also suggested that the information presented in this visualization may have overwhelmed the participants. This suggestion was explored in the final visualization, which featured colored contaminants.

4.2.5 3D, Static with Surface/Subsurface and Color Contamination

The fifth and final new karst visualization was identical to the fourth visualization accept with the addition of pink color to the rainwater and white color to the disappearing stream to represent contamination. KDE results for the participants that viewed the karst visualization show regions of interest (ROI) or “hotspots” where the participants spent longer portions of time viewing specific areas of the visualization (Figure 4.33, Appendix C Figure 17)**.** The highest concentration of hotspots or fixations of participants that viewed the karst visualization focused on the where the “surface & subsurface interaction” label points inside the visualization. Other, less concentrated fixations occurred on the right house and the start of the disappearing stream behind it, the sinkhole area where the disappearing stream entered the subsurface, the rainwater stream to the left with its directional arrows and the pink contamination that fell down with it inside the left conduit, the car, the waterfall coming down into the subsurface, conduits on the right side of the visualization, and the conduit where the “cave” label is pointing to in the visualization. Additionally, minor fixations occurred on the “soil”, “cave”, “groundwater”, and “limestone” labels.

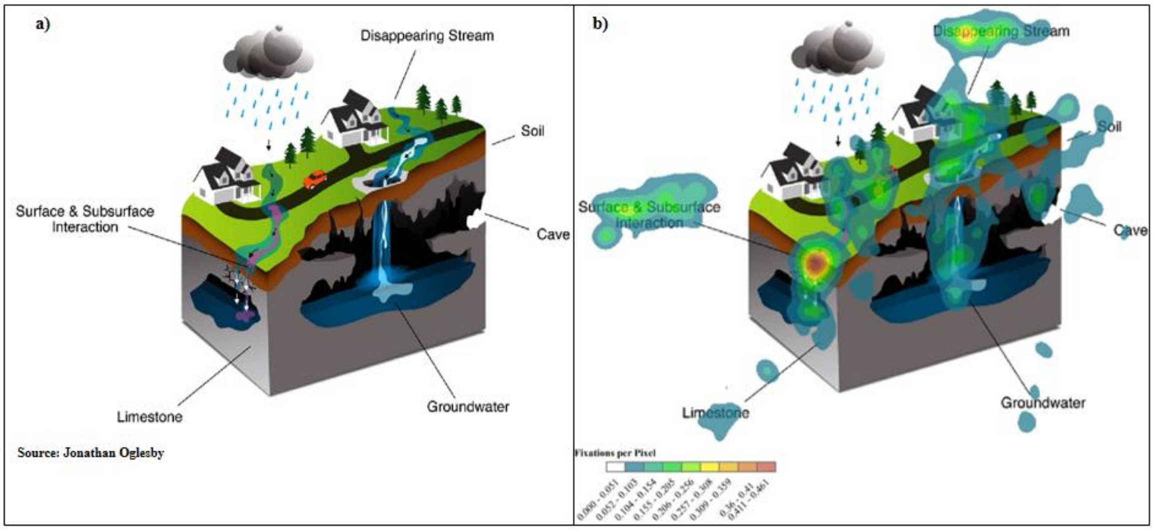


Figure 4.33. a) 5th new karst visualization b) KDE results of NPGL5.

The pre- and post-assessments, semi-structured interview data, and quantitative eye-tracking KDE analysis reveal this visualization was helpful to participants without prior karst knowledge especially in terms identifying contamination sources. The most notable differences in learning outcomes between the pre- and post-assessments occurred on PostQ4 with 20% of participants answering partial correctly and 50% of participants explaining different contaminants that affect a karst landscape, on PostQ5 with 100% of participants answering correctly why karst landscapes lack surface water, PostQ6 with 40% of participants partial correctly and 40% of participants correctly identifying karst features, and PostQ7 with 60% of participants answering correctly the primary cause of karst or cave formation (Figure 4.34, Appendix D Table 17). A Wilcoxon signed-rank sum, two-tailed test was performed on the PreQ6 and PostQ6 and showed statistically significant differences between participants' responses for PreQ6 and PostQ6 ($p < 0.012$).

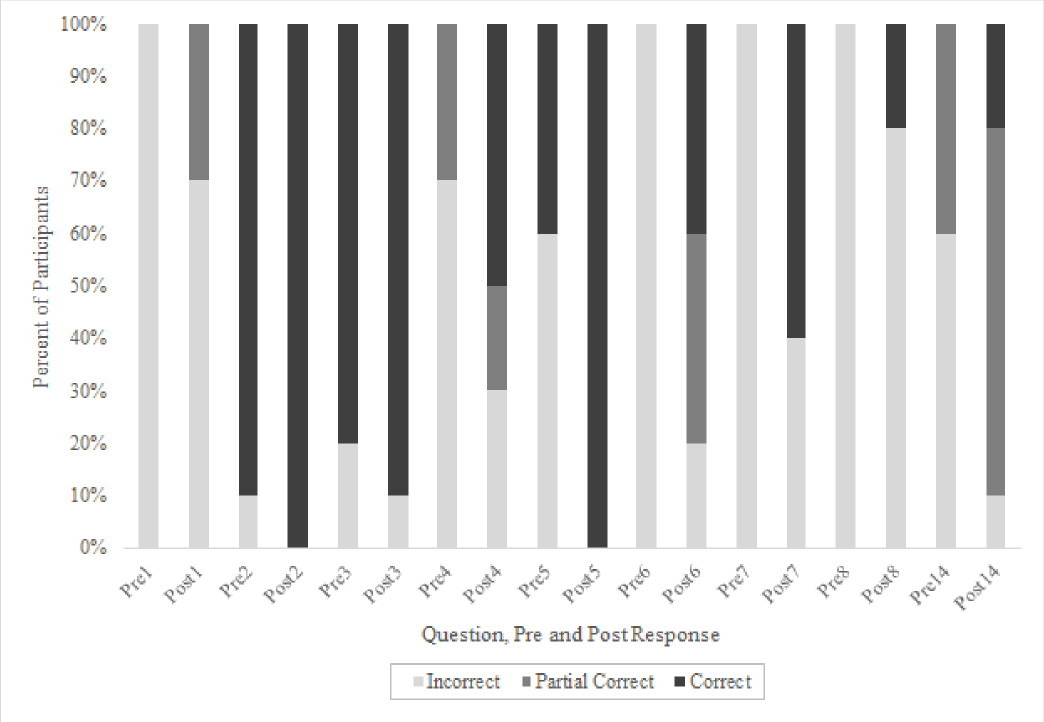


Figure 4.34. Pre- and post-responses of NPGTL5 participants.

This visualization caused very notable differences in pre- and post-assessment learning outcomes in reference to karst contamination from participants on PostQ4, which could due to the addition of color pink color added to the rainwater and white color that was added to the disappearing stream to represent contamination. However, when participants were shown a visualization that featured colored contamination, interestingly, 9 out of the 10 participants did not notice the addition of color when asked about it in the semi-structured interview. Nonetheless, the results the post-assessments and interviews from participants that viewed the visualization suggest that these participants were able to reveal many more example of contaminants in a karst landscape than any other small group or large group trial. However, more participants that did not view sources of contamination in the large group trials answered more partial correctly and correctly how the surface and subsurface are connected in a karst landscape. Additionally, the results of this trial suggest the visualization developers need to clearly understand the topics they are trying to convey before developing a scientific visualization. Furthermore, visualization developers should not overwhelm observers with too much information and should only focus on one or two concepts in a scientific visualization. Visualization developers need to be aware of this definite trade-off that exists between overloading an observer with too many concepts and just creating enough detail in a visualization that conveys one or two focused concepts.

4.3 Summary

By using the small group experiments as pilot studies to look for knowledge outcome trends among the manipulated visual stimuli categories in pre-existing karst visualizations, it was possible to form an educated and informed approach to developing new karst visualizations that produced higher learning outcomes and genuinely improved the participants understanding of karst landscapes, especially when compared to pre-existing karst visualizations. From the combined results from both trials the following features were determined to be the key features and concepts to incorporate into a karst visualization to make it effective at communicate karst concepts:

1. Indicate directionality of water moving through the karst landscape by arrows
2. Add color and contrast to important features in the karst visualization (i.e., water, soil, and limestone)
3. Use 3D, static orientation to allow the participant to view every angle of a karst landscape and how water moves through it
4. Pay attention to label placement and content in terms of placing labels outside of the visualization to allow participants to view features within the visualization
5. Make sure labels are conveying the appropriate concepts
6. Use a minimalistic approach to avoid distracting observers with less important karst features
7. Make sure to establish the goal of the karst visualization before creating it, and make sure the concepts presented will not be overwhelming to the participant

The data collected in this study suggest that by following these recommendations, an observer is more likely to learn about karst landscapes. Specifically, the observer is likely to understand the connectivity of the surface and subsurface in a karst landscape. Additionally, the results of this study build upon studies that suggest the educational effectiveness of leader lines and color (Griffin and Robinson 2010) and the need for visualization developers to consider label placement and content (Bothelo and Morais

2005), and also help bridge the gap between learning outcomes that can be achieved by observers viewing 2D versus 3D oriented visualizations (Reynolds et al. 2005).

Lastly, the study not only provided insight on how to develop karst visualizations, but study also developed and tested a research methodology framework that can allow for important research questions to be qualitatively and quantitatively answered about broader scientific topics that are conveyed using scientific visualizations. This research methodology framework has already been adopted by colleagues to perform similar projects related to karst environments and the interpretation of signs.

CHAPTER FIVE: CONCLUSIONS AND FUTURE RESEARCH

5.1 Conclusions

Karst landscapes are interconnected, vulnerable environments that provide not only 20-25% of the world with drinking water, but also supply valuable fossil fuels and minerals and have unique biota and features. However, in many cases, regulatory protection for karst landscapes is unavailable mainly due to monetary and time constraints of public administrators to properly manage the karst environments (North 2011). Thus, the primary cost-effective way to minimize occurrences of anthropogenic karst disturbance is through educational pursuits, which communicate to the public about the importance of karst landscapes. Yet, these educational pursuits can often be hindered by trying to convey the complexity and interactions of karst environments that often occur underground and are not easily visible to the general public. Educational pursuits try to convey these complex concepts to the general public in the form of diagrams, photographs, and/or infographics. However, many of these pursuits distribute karst visualizations that can be ineffective or inaccurate. This study developed a triangulated approach to assess the effectiveness of pre-existing karst visualizations and create new, effective visualization to distribute to the general public.

Through the use of stationary eye-tracking and assessment techniques, results from this research included the quantification of attention paths and fixations of observers with and without prior geoscience knowledge and identification of the most effective visual stimuli and characteristics for learning through karst visualizations. Furthermore, this technique allowed learning outcomes to be analyzed for five newly developed karst visualizations that were created as a result of the eye-tracking trials that explored the most effective visual stimuli used in pre-existing karst visualizations.

Over the course of this study, 18 different stationary eye-tracking trials were conducted with a total of 135 participants. The trials consisted of small group experiments that were used as a pilot study to determine the most educationally effective visual stimuli in pre-existing karst visualizations (n = 60), an expert trial that allowed for the study of eye movement scan paths of geoscience experts versus non-geoscience experts (n=10), and large group trials that analyzed five newly developed karst visualizations, which were created based on the combined effective stimuli from the small group experiments.

From the results of all of these trials, seven key characteristics and concepts for developing effective karst visualizations were found: indicate directionality of water with arrows; add color contrast to important features; use 3D, static orientation; cautiously use labels and be cognizant of label placement; avoid distraction by using a minimalistic approach; establish a clear goal of the visualization before creating it; and teach no more than two new concepts. These seven proven key characteristics and concepts for karst visualization creation should help to ensure the development of new tools that, with scientific certainty, are effectively and efficiently communicating about karst and groundwater to non-karst experts. Furthermore, based on these key characteristics and concepts for karst visualization, five new karst visualizations were created and analyzed with results that showed overwhelmingly high learning outcomes. The results from the five newly developed studies suggest that all of these karst visualization can be deemed effective and are suitable for distribution to the general public.

In addition to the seven key characteristics and concepts for developing karst visualizations, this study developed a revolutionary framework for assessing the effectiveness of any type of scientific visualizations. The methodology alone from this study should be taken as best practices for conducting a successful study on the educational effectiveness and design of future scientific visualizations. By using a mixed-methods approach to develop a triangulated research design framework for educational research, this study provided a foundation integrated with robust quantitative and qualitative data collection methods for future scientific visualization and educational studies to be based upon. With the adoption of this approach, educational research studies can have the statistical strength to be accepted in larger scientific communities, which can lead to many more multi-collaborative projects between the physical, psychological, and educational sciences.

Dissemination of the results of this study has already occurred at the Geological Society of America 2013 Conference, the Western Kentucky University Student Research Conference 2014, and the Association of American Geographers 2014 Conference, and will be further disseminated through publication in a peer-reviewed journal. All findings, along with created 2D and static 3D infographics and diagrams, will be submitted to the Karst Information Portal, which is a readily used, open-access digital library for research regarding karst and water resources. This and other outlets will allow researchers, educators, and interpreters worldwide to access and distribute proven-effective karst educational materials to the public. With time, these materials have the ability to encourage attitude and behavior changes, decrease occurrences of anthropogenic disturbance, and even increase demand for karst regulations and protection. By serving as a general framework for the development of educational karst materials for use in classrooms, textbooks, museums, science centers, show caves, and beyond, conclusions may be drawn from the results of this study that continue to achieve these goals. In addition to sharing findings from this study on a global scale, efforts will be made locally to share findings with local show cave operators and educators.

5.2 Future Research

Many future studies are possible by building upon this pioneer study. However, the author has three important suggestions listed in this section for future studies that have the greatest potential for their successful completion.

The population of this study was limited to college students, due to the locational convenience and access to a large participant pool. Future karst visualization eye-tracking research should find ways to recruit participants and go out in the community to find a more representative population of the "general public." Increasing the diversity of the sample population would allow for research questions to be answered regarding the interpretation of karst visualizations by a wider-audience that could correspond, for example, to people who visited show caves (i.e. from elementary school students to middle-aged tourists).

When asked to suggest improvements for the karst visualization used in these trials, many participants suggested that interaction, movement, and/or sound would really help them in understanding more about karst landscapes. Future eye-tracking karst visualization studies should focus on interactive, 3D karst digital models, interactive show cave exhibits, and even interactive show cave tours that could even be investigated using a mobile eye-tracker. By adding the element of interaction to karst visualizations, research questions could be investigated on the educational learning outcome differences of using static as opposed to interactive karst visualizations. Additionally, the educational effectiveness of interaction characteristics could be explored - such as mouse clicks, the use of a touch-screen device, and sound.

This study showed trends that the scanpaths of non-prior-geoscience participants versus karst experts can be very different. For example, when non-geoscience experts viewed the NPGT1 karst visualization without arrows, their scanpaths showed trends of being very scattered (Appendix D, Figure 18). However, when the same visualization was presented to karst experts, their scanpaths showed a focus that followed the cracks and crevices of rain entering a karst landscape. These trends alone suggest the need for using non-geoscience participants to help develop karst visualizations. However, further study is needed to look at and document these differences in more depth to distribute these results confidently to the scientific community.

APPENDIX A: SURVEY INSTRUMENTS

Small Group Experiments Pre-Assessment

1. Have you ever heard of the word "**karst**" before? If you have, please define the word **karst** or describe a **karst landscape.**

2. What type of rock do caves in Kentucky primarily form?
    a. Sandstone
    b. Limestone
    c. Shale
    d. Volcanic Rock

3. How do humans impact karst groundwater resources in terms of quality of the water and amount of water?

4. Why do karst landscapes often lack surface water?
    a. Lack of precipitation
    b. Surface water sinks below the surface into conduits
    c. The dry surface evaporates the surface water
    d. None of the above

5. List the main features of a karst landscape.

6. The chemical weathering process of limestone caused by groundwater that causes rock materials and minerals to be carried away in solution, is called:
    a. precipitation
    b. dissolution
    c. hydration
    d. infiltration

7. How are the surface and subsurface connected in a karst landscape?

8. Carbonic acid, the primary source of chemical weathering in limestone is produced by:
    a. carbon dioxide dissolved in rainwater
    b. plant and animal remains found in soil
    c. bacteria that feed on plant and animal remains
    d. all of the above

9. What are the major contaminants that impact a karst system?

10. What is your age?
    a. 18-24 years old
    b. 25-34 years old
    c. 35-44 years old

    d. 45-54 years old
    e. 55-64 years old
    f. 65-74 years old
    g. 75 years or older

11. What is your gender?
    a. Male
    b. Female

12. Please specify your ethnicity:
    a. White
    b. Hispanic or Latino
    c. Black or African American
    d. Native American or American Indian
    e. Asian / Pacific Islander
    f. Other

13. What is the highest level of school your have completed?
    a. High school graduate, diploma or the equivalent (ex: GED)
    b. Some college credit, no degree
    c. Trade/technical/vocational training
    d. Associate degree
    e. Bachelor’s degree

14. Do you have experience learning about karst and cave environments? If so, where and what concepts did you learn about these types of environments?

15. Do you believe that karst and cave regulations and protection are important? If so, why?

Small Group Experiments Post-Assessment

1. Have you ever heard of the word "**karst**" before? If you have, please define the word **karst** or describe a **karst landscape.**
2. What type of rock do caves in Kentucky primarily form?
   a. Sandstone
   b. Limestone
   c. Shale
   d. Volcanic Rock
3. How do humans impact karst groundwater resources in terms of quality of the water and amount of water?
4. Why do karst landscapes often lack surface water?
   a. Lack of precipitation
   b. Surface water sinks below the surface into conduits
   c. The dry surface evaporates the surface water
   d. None of the above
5. List the main features of a karst landscape.
6. The chemical weathering process of limestone caused by groundwater that causes rock materials and minerals to be carried away in solution, is called:
   a. precipitation
   b. dissolution
   c. hydration
   d. infiltration
7. How are the surface and subsurface connected in a karst landscape?
8. Carbonic acid, the primary source of chemical weathering in limestone is produced by:
   a. carbon dioxide dissolved in rainwater
   b. plant and animal remains found in soil
   c. bacteria that feed on plant and animal remains
   d. all of the above
9. What are the major contaminants that impact a karst system?
10. Do you believe that karst and cave regulations and protection are important? If so, why?

Large Group Trials Pre-Assessment

1. Have you ever heard of the word "**karst**" before? If you have, please define the word **karst** or describe a **karst landscape.**

2. What type of rock do caves in Kentucky primarily form in?
   a. Sandstone
   b. Limestone
   c. Shale
   d. Volcanic Rock

3. Water that is stored below the water table in the zone of saturation is called:
   a. Soil moisture
   b. Groundwater
   c. Artesian water
   d. Salt water

4. What human actions impact karst water resources in terms of the quality of the water and amount of water? What are some sources of contaminants? **Please be specific as possible.**

5. Why do karst landscapes often lack surface water?
   a. Lack of precipitation
   b. Surface water sinks below the surface into conduits
   c. The dry surface evaporates the surface water
   d. None of the above

6. List the main features of a karst landscape.

7. What primarily causes karst or cave formation in sedimentary rock?

8. How are the surface and subsurface connected in a karst landscape?

9. What is your gender?
   a. Male
   b. Female

10. What is your age?
    a. 18-24 years old
    b. 25-34 years old
    c. 35-44 years old
    d. 45-54 years old
    e. 55-64 years old
    f. 65-74 years old
    g. 75 years or older

11. Please specify your ethnicity:
    a. White
    b. Hispanic or Latino
    c. Black or African American
    d. Native American or American Indian
    e. Asian / Pacific Islander
    f. Other

12. What is the highest level of school your have completed?
    a. High school graduate, diploma or the equivalent (ex: GED)
    b. Some college credit, no degree
    c. Trade/technical/vocational training
    d. Associate degree
    e. Bachelor’s degree

13. Do you have experience learning about karst and cave environments? If so, where and what concepts did you learn about these types of environments?

14. Do you believe that karst and cave regulations and protection are important? If so, why?

Large Group Trials Post-Assessment

1. Please define the word **karst** or describe a **karst landscape.**

2. What type of rock do caves in Kentucky primarily form in?
    a. Sandstone
    b. Limestone
    c. Shale
    d. Volcanic Rock

3. Water that is stored below the water table in the zone of saturation is called:
    a. Soil moisture
    b. Groundwater
    c. Artesian water
    d. Salt water

4. What human actions impact karst water resources in terms of the quality of the water and amount of water? What are some sources of contaminants? **Please be specific as possible.**

5. Why do karst landscapes often lack surface water?
    a. Lack of precipitation
    b. Surface water sinks below the surface into conduits
    c. The dry surface evaporates the surface water
    d. None of the above

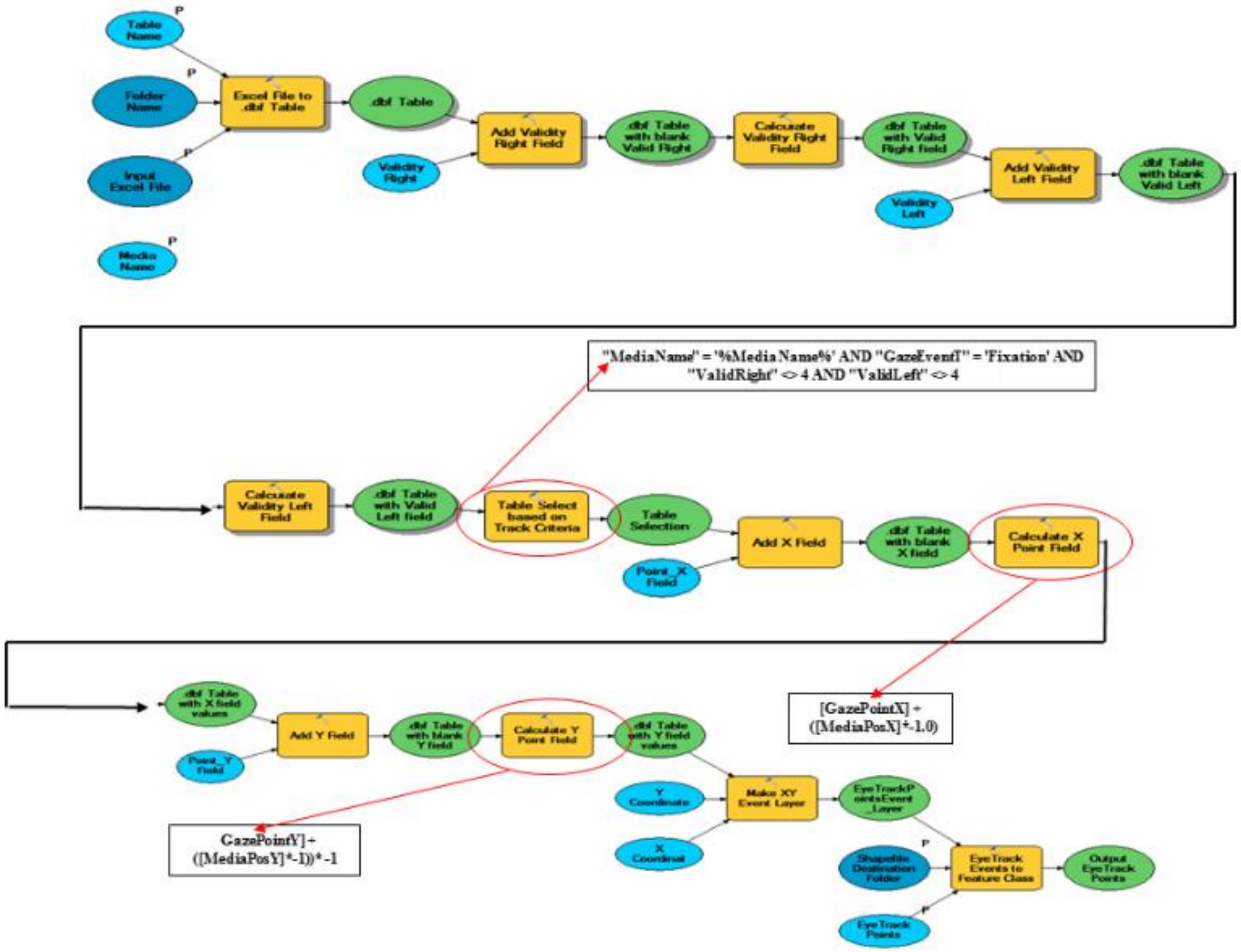
6. List the main features of a karst landscape.

7. What primarily causes karst or cave formation in sedimentary rock?

8. How are the surface and subsurface connected in a karst landscape?

9. Do you believe that karst and cave regulations and protection are important? If so, why?

APPENDIX B: CUSTOM ARCGIS EYE-TRACKING MODEL



APPENDIX C: RAW EYE-TRACKING DATA

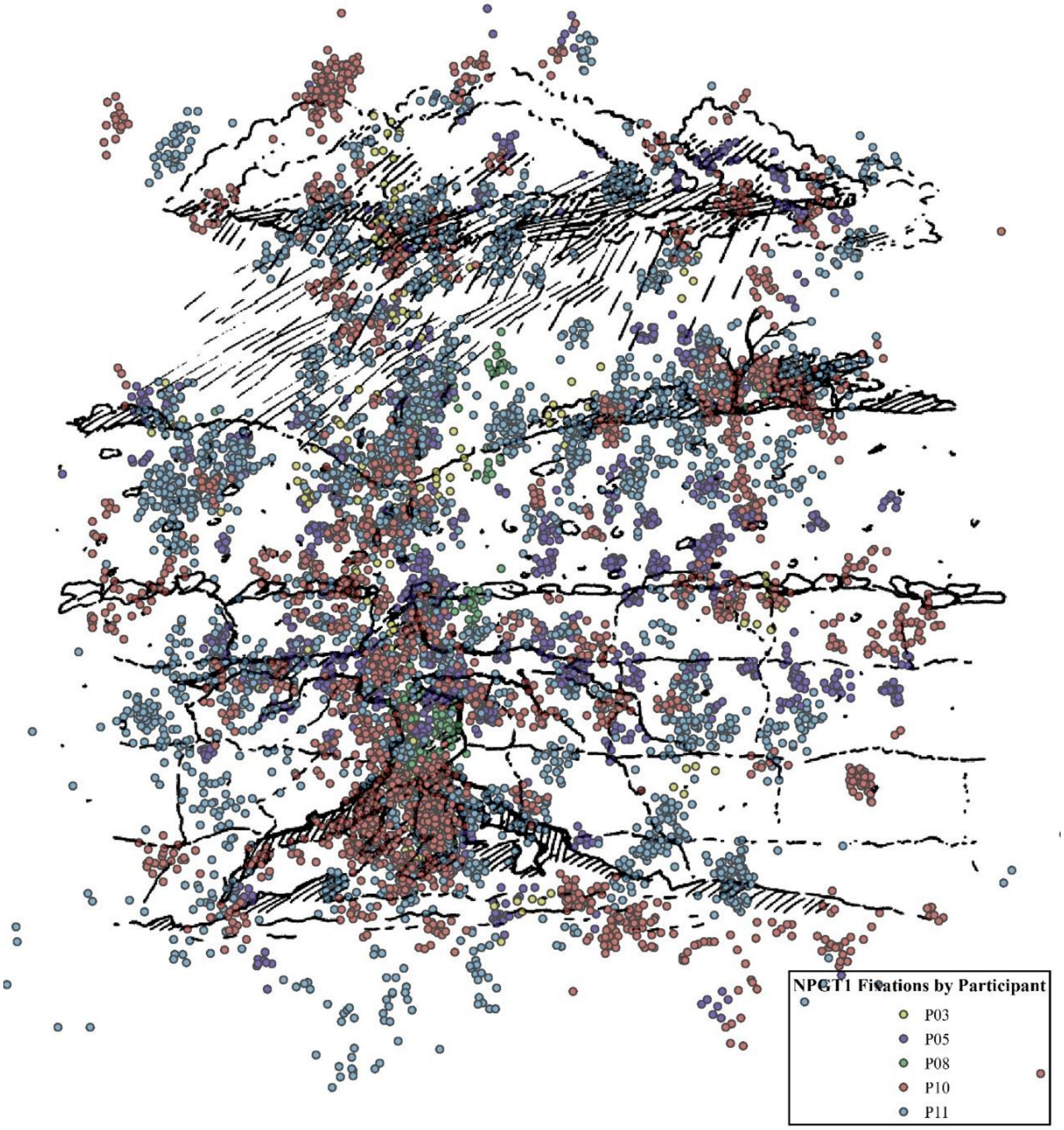


Figure 1. Raw fixation equal interval gaze point coordinates plotted for all participants in NPGT1

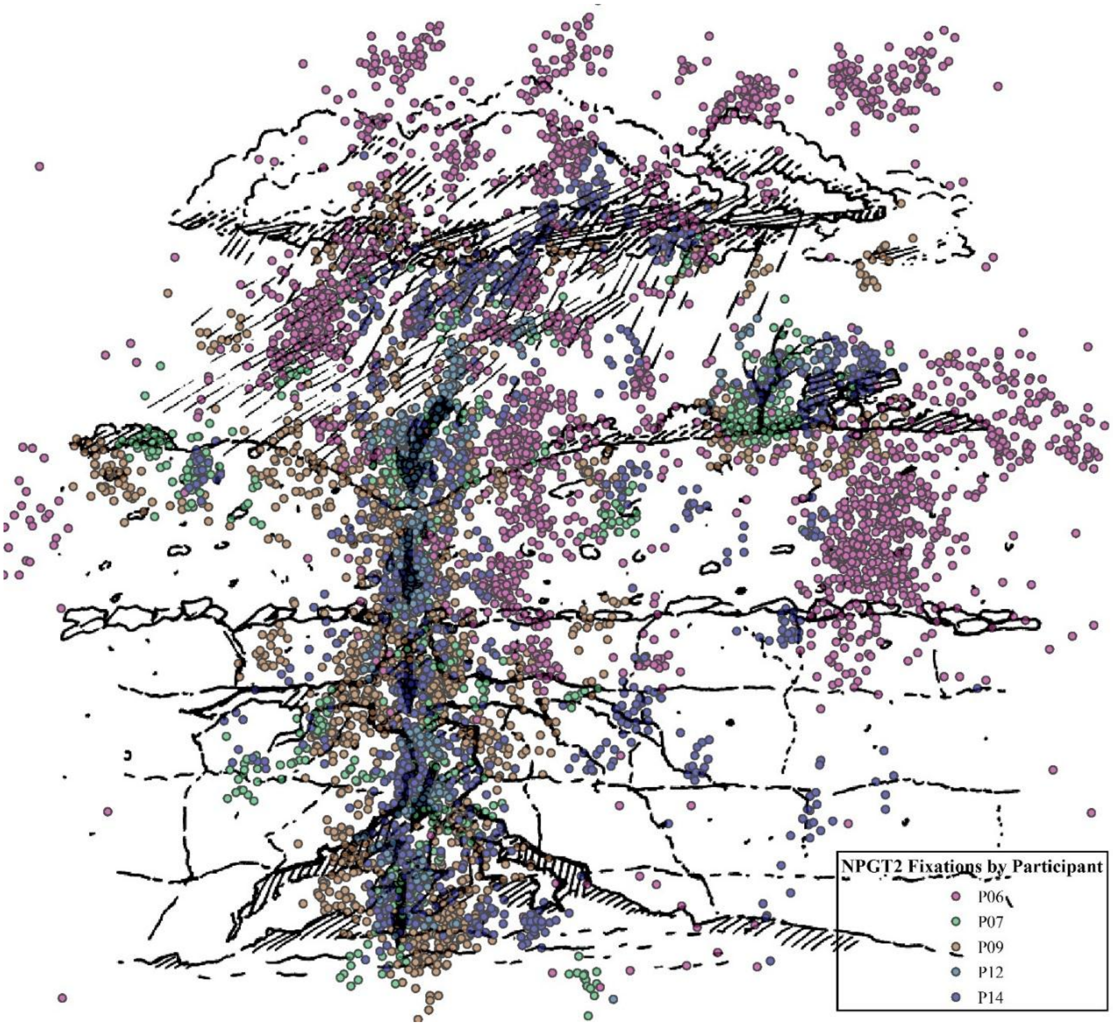


Figure 2. Raw fixation equal interval gaze point coordinates plotted for all participants in NPGT2

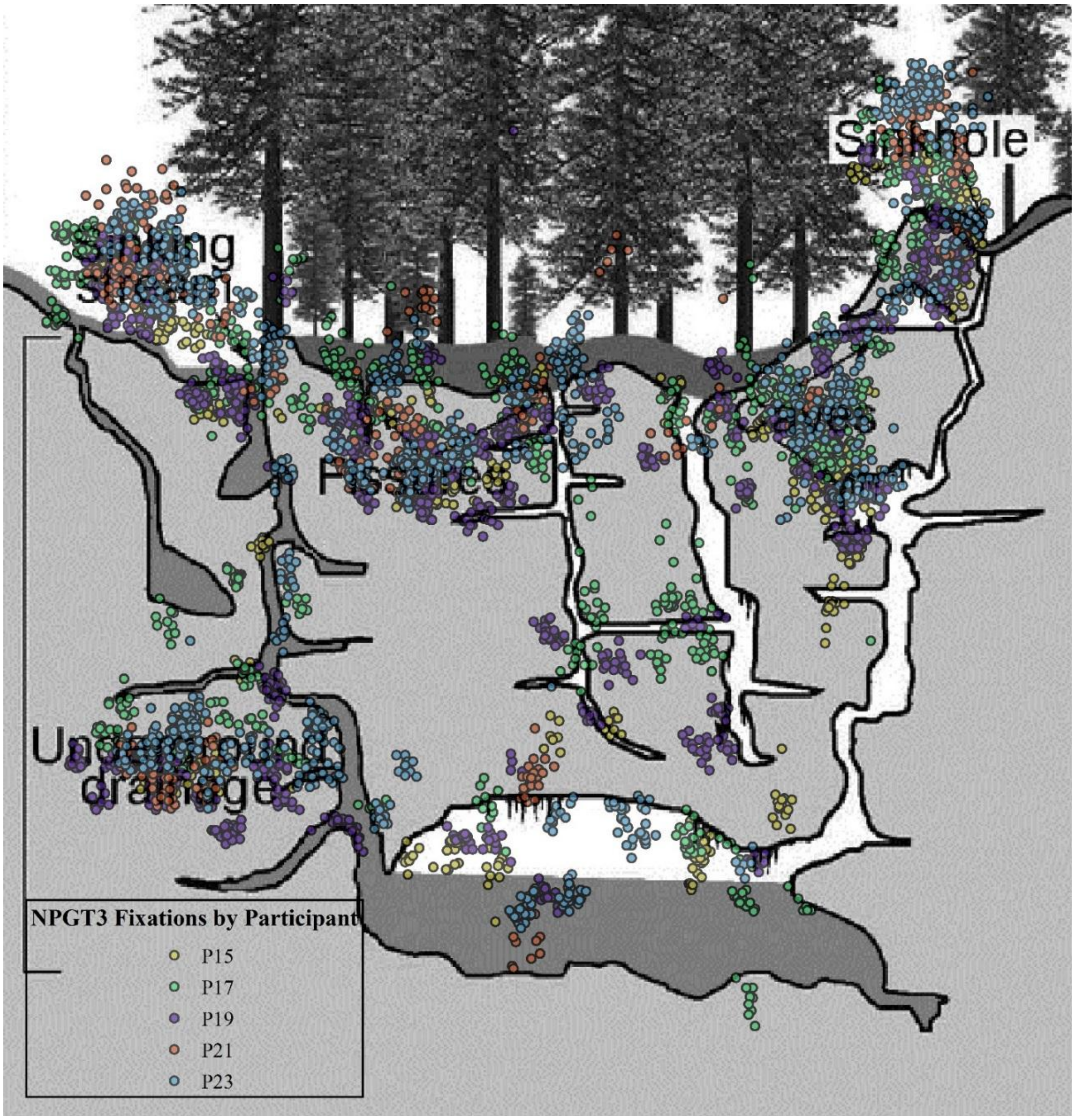


Figure 3. Raw fixation equal interval gaze point coordinates plotted for all participants in NPGT3

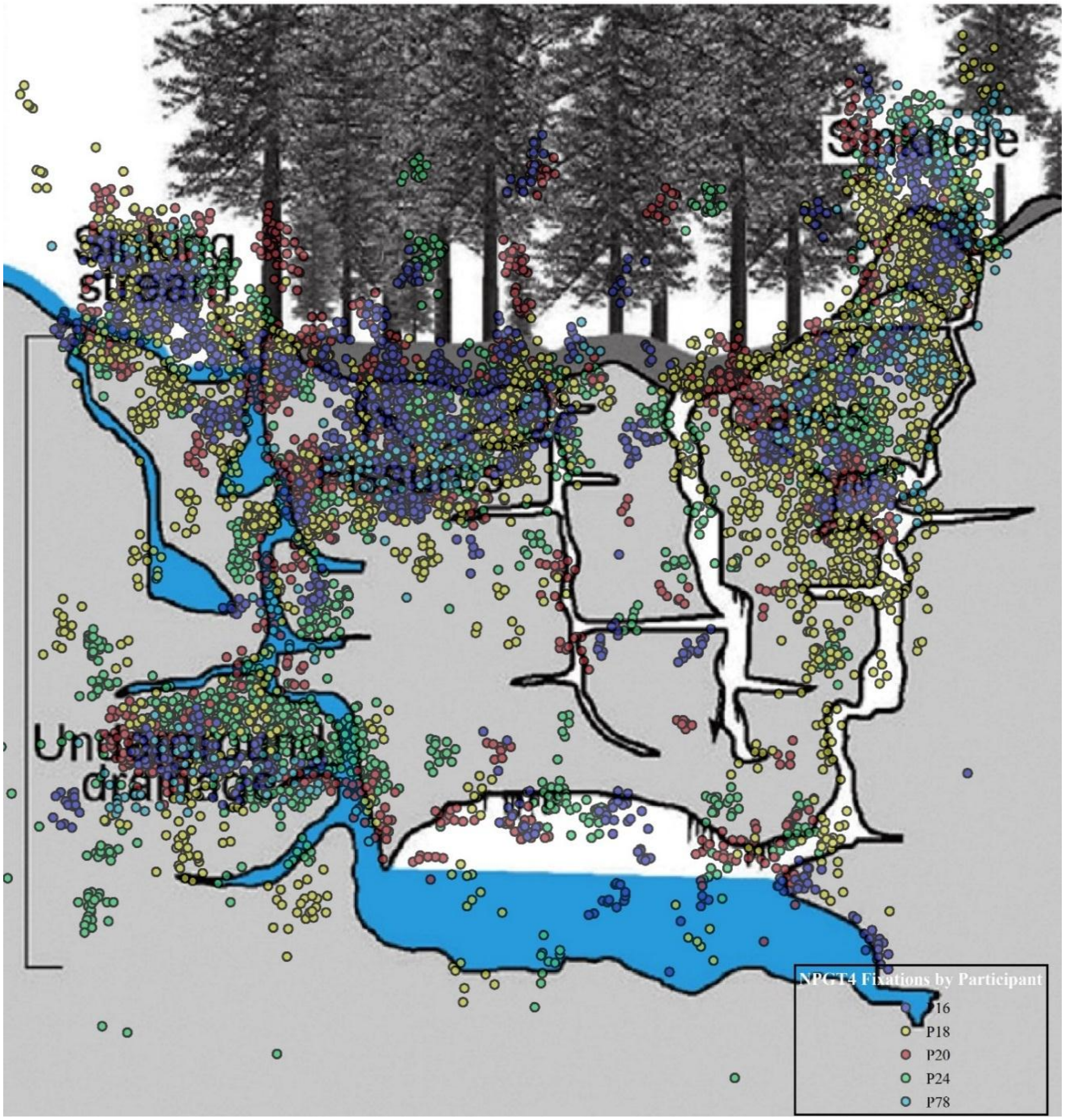


Figure 4. Raw fixation, equal interval gaze point coordinates plotted for all participants in NPGT4

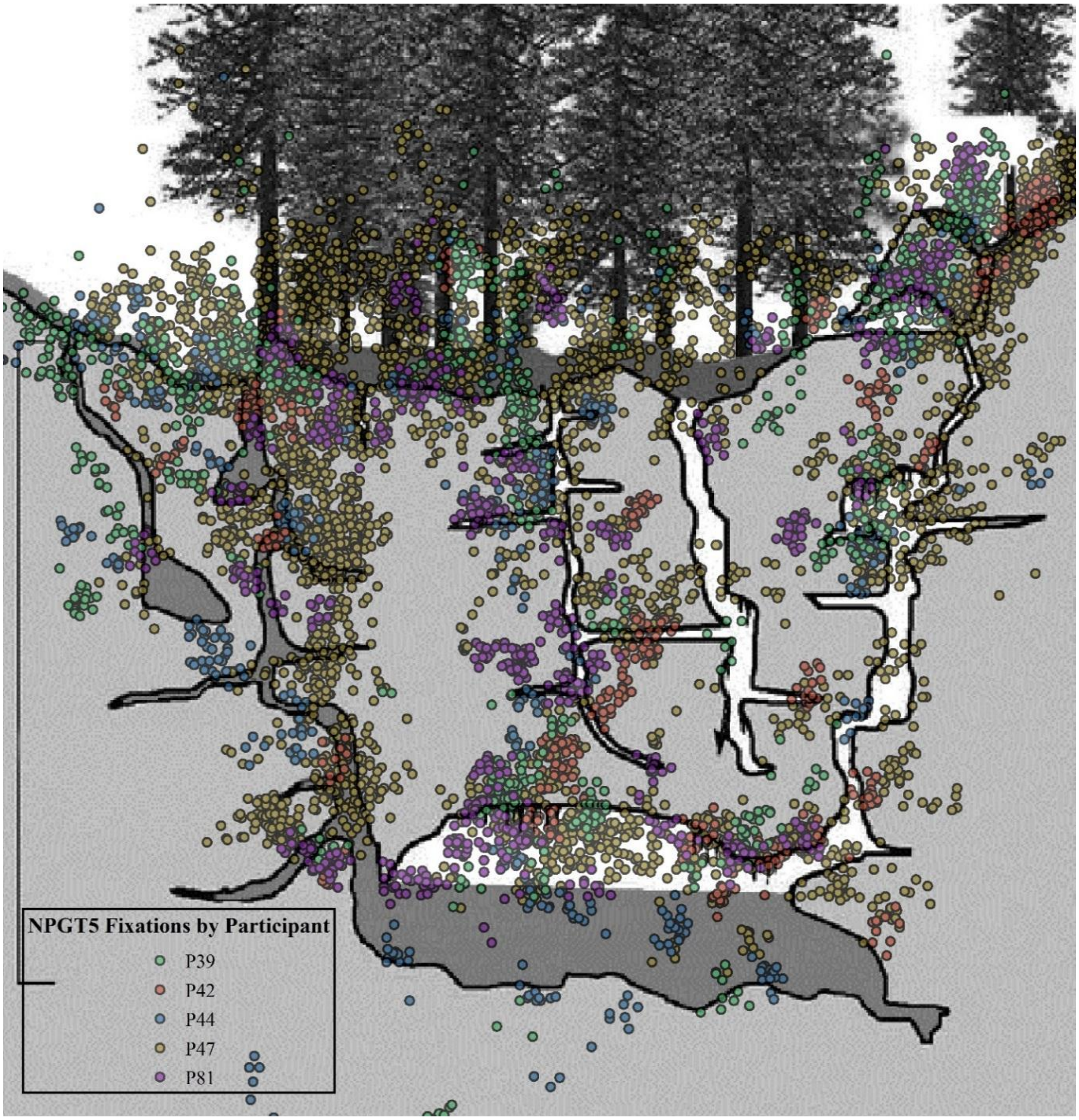


Figure 5. Raw fixation, equal interval gaze point coordinates plotted for all participants in NPG5

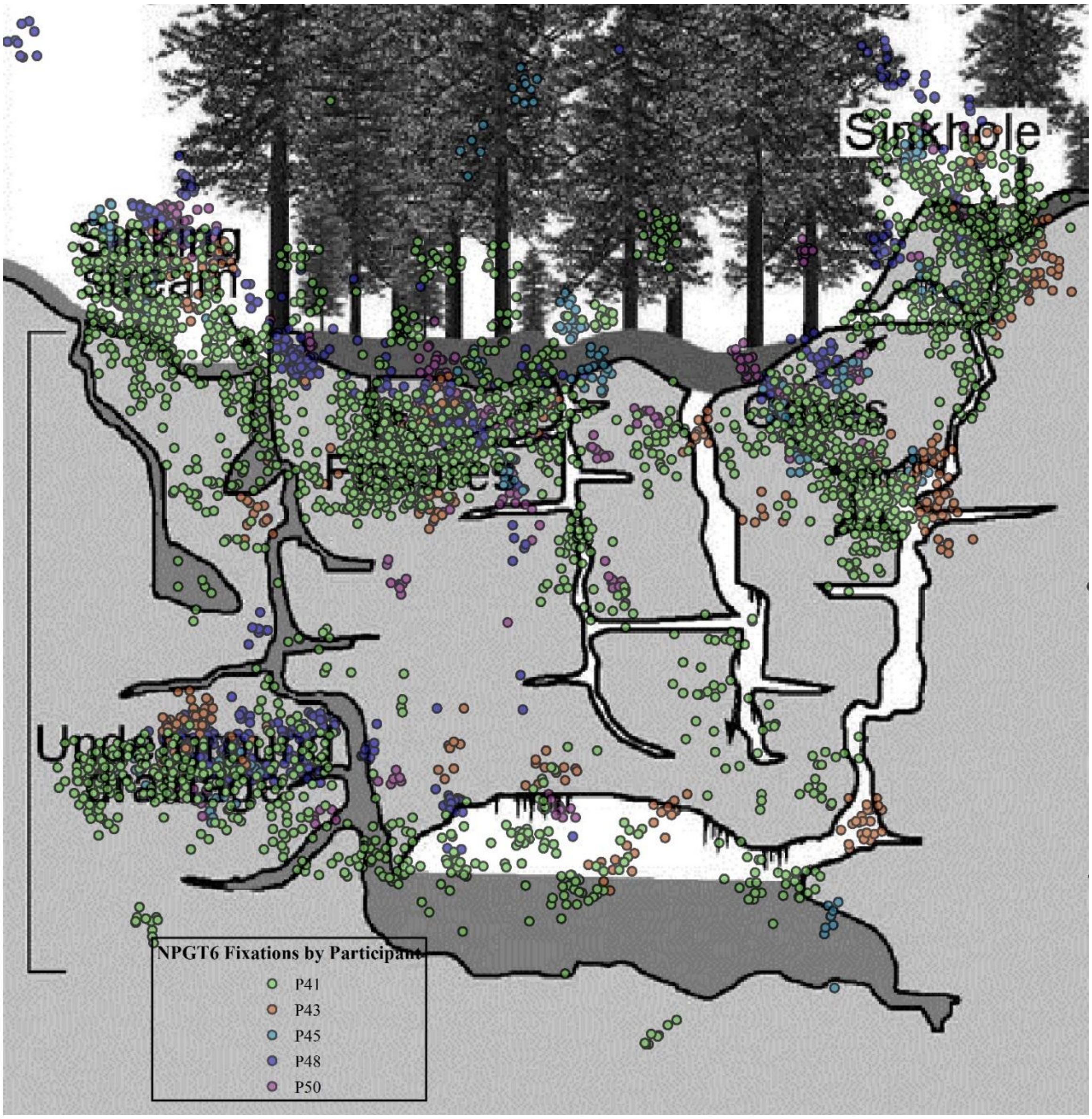


Figure 6. Raw fixation, equal interval gaze point coordinates plotted for all participants in NPGT6

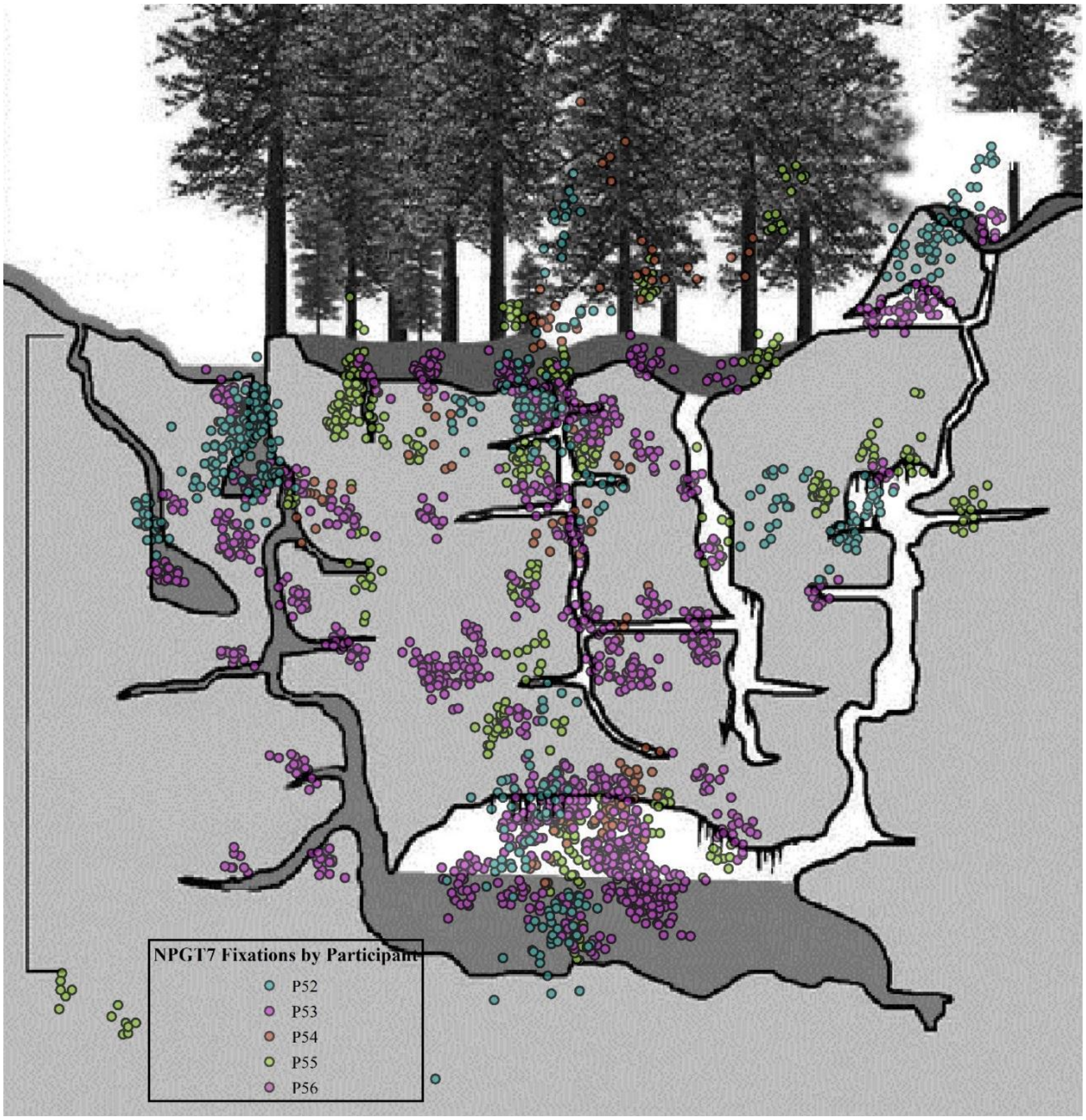


Figure 7. Raw fixation, equal interval gaze point coordinates plotted for all participants in NPGT7

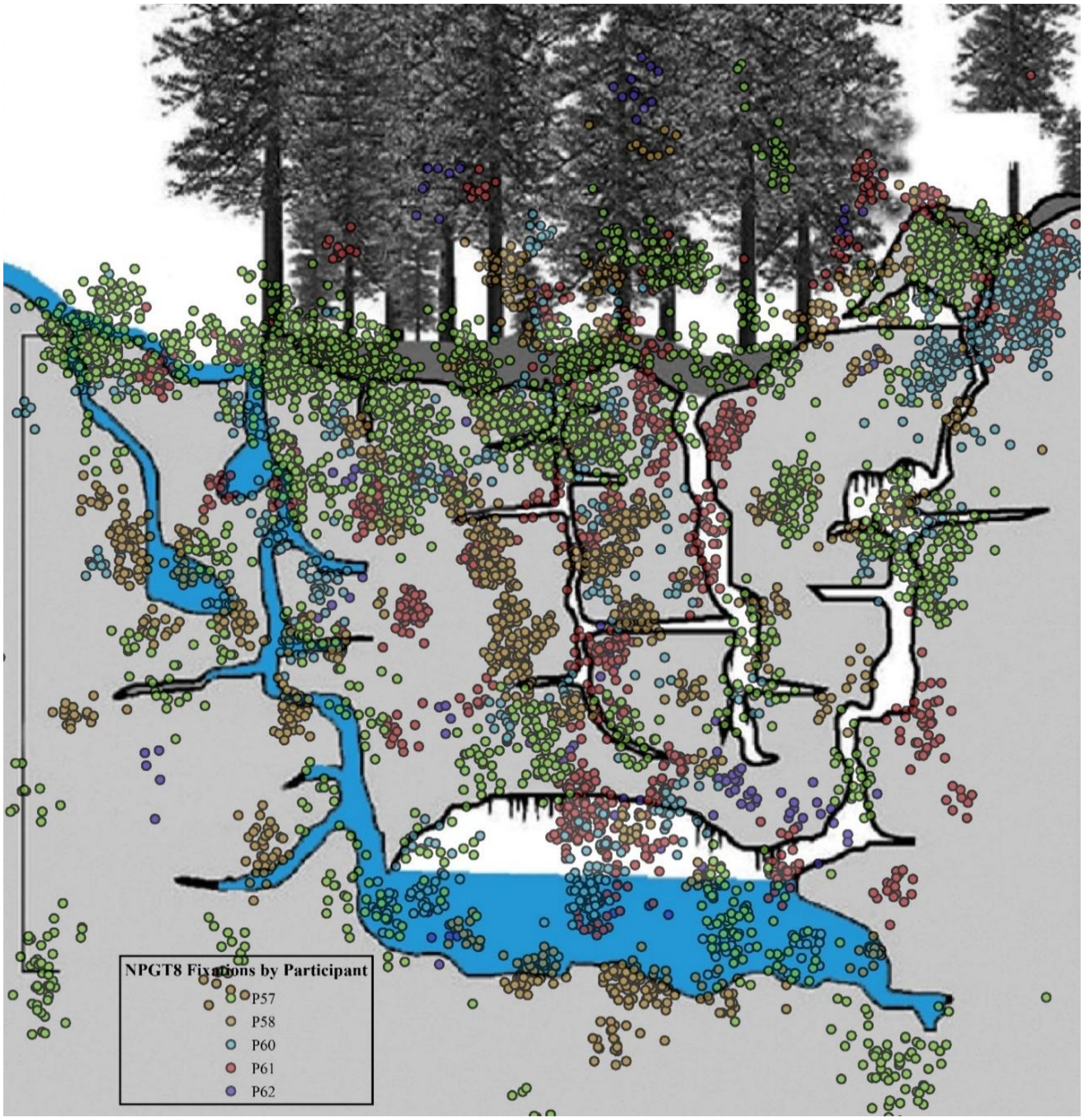


Figure 8. Raw fixation, equal interval gaze point coordinates plotted for all participants in NPGT8

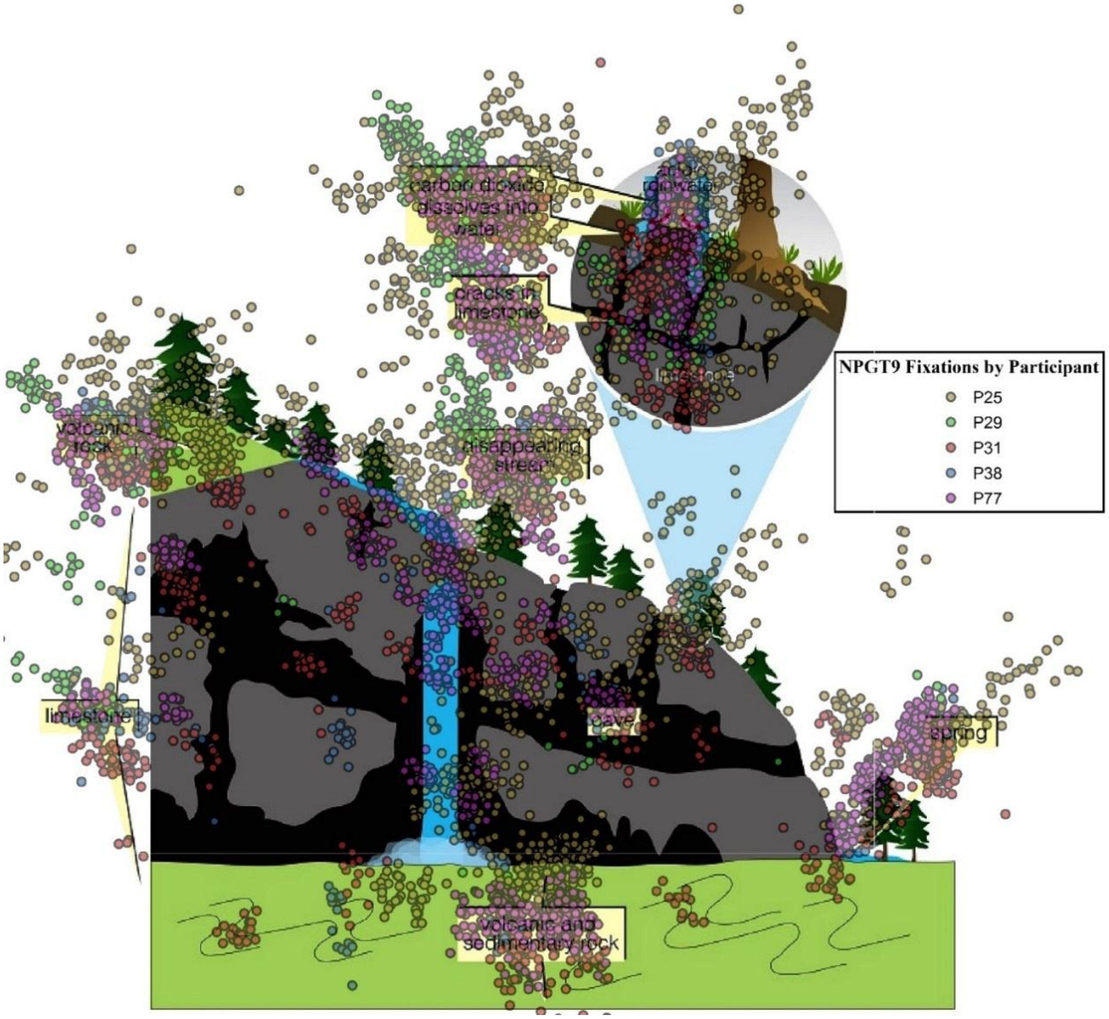


Figure 9. Raw fixation, equal interval gaze point coordinates plotted for all participants in NPGT9

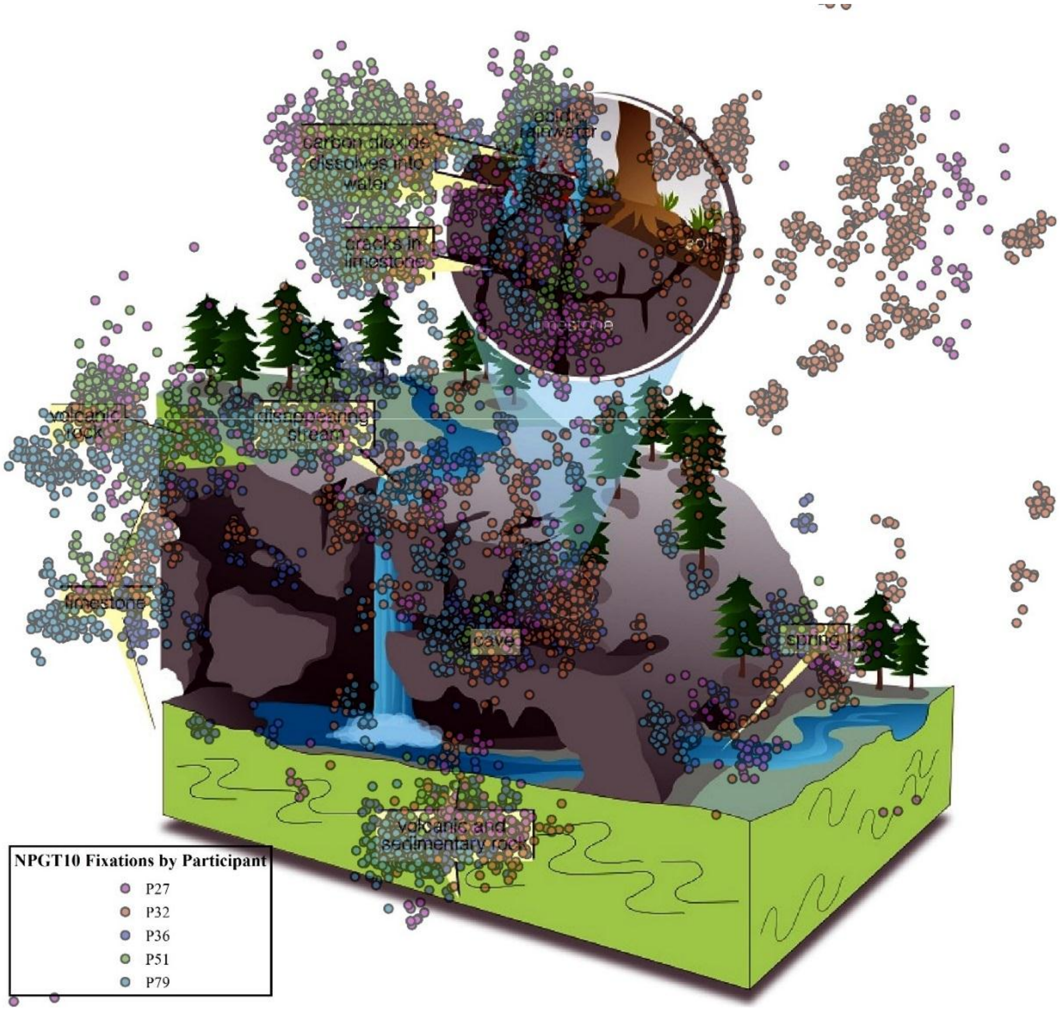


Figure 10. Raw fixation, equal interval gaze point coordinates plotted for all participants in NPGT10

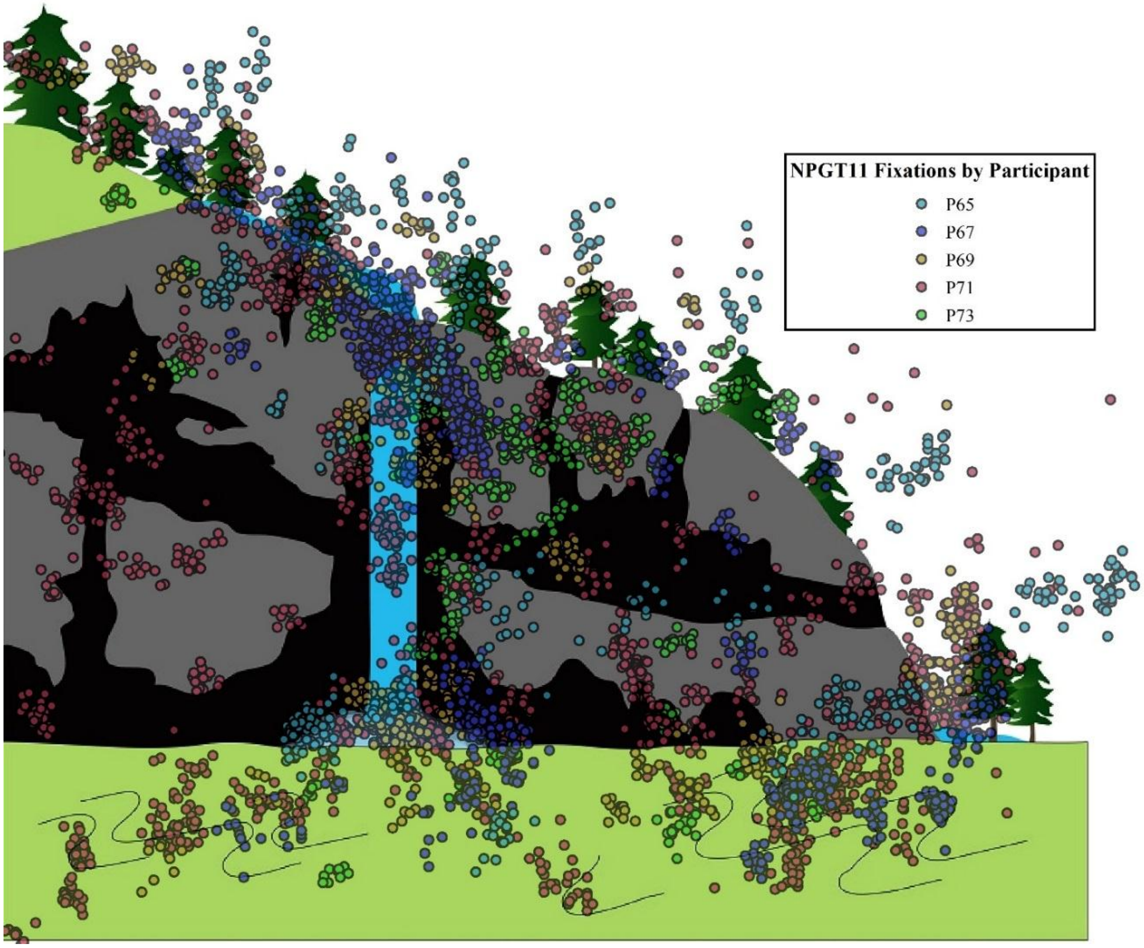


Figure 11. Raw fixation, equal interval gaze point coordinates plotted for all participants in NPGT11

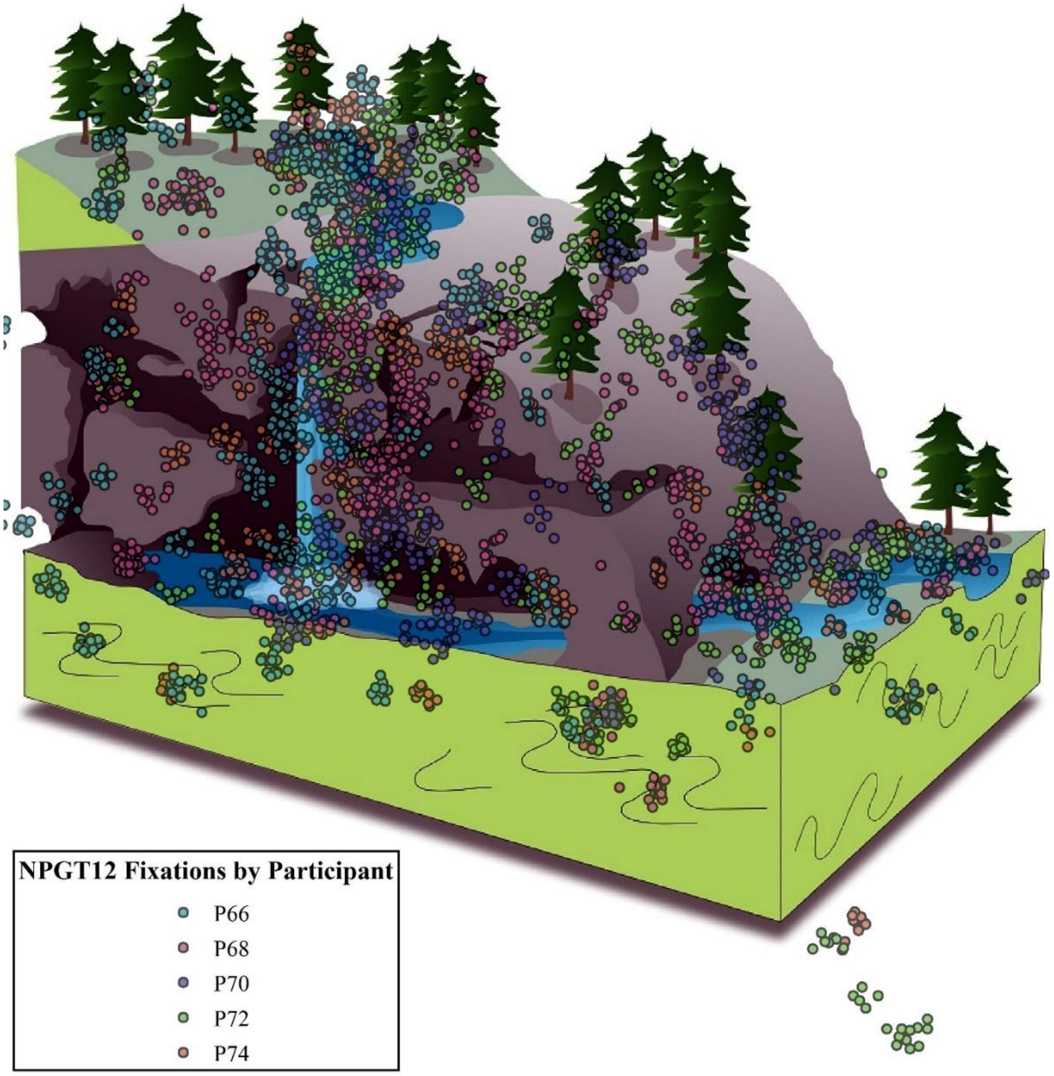


Figure 12. Raw fixation, equal interval gaze point coordinates plotted for all participants in NPGT12

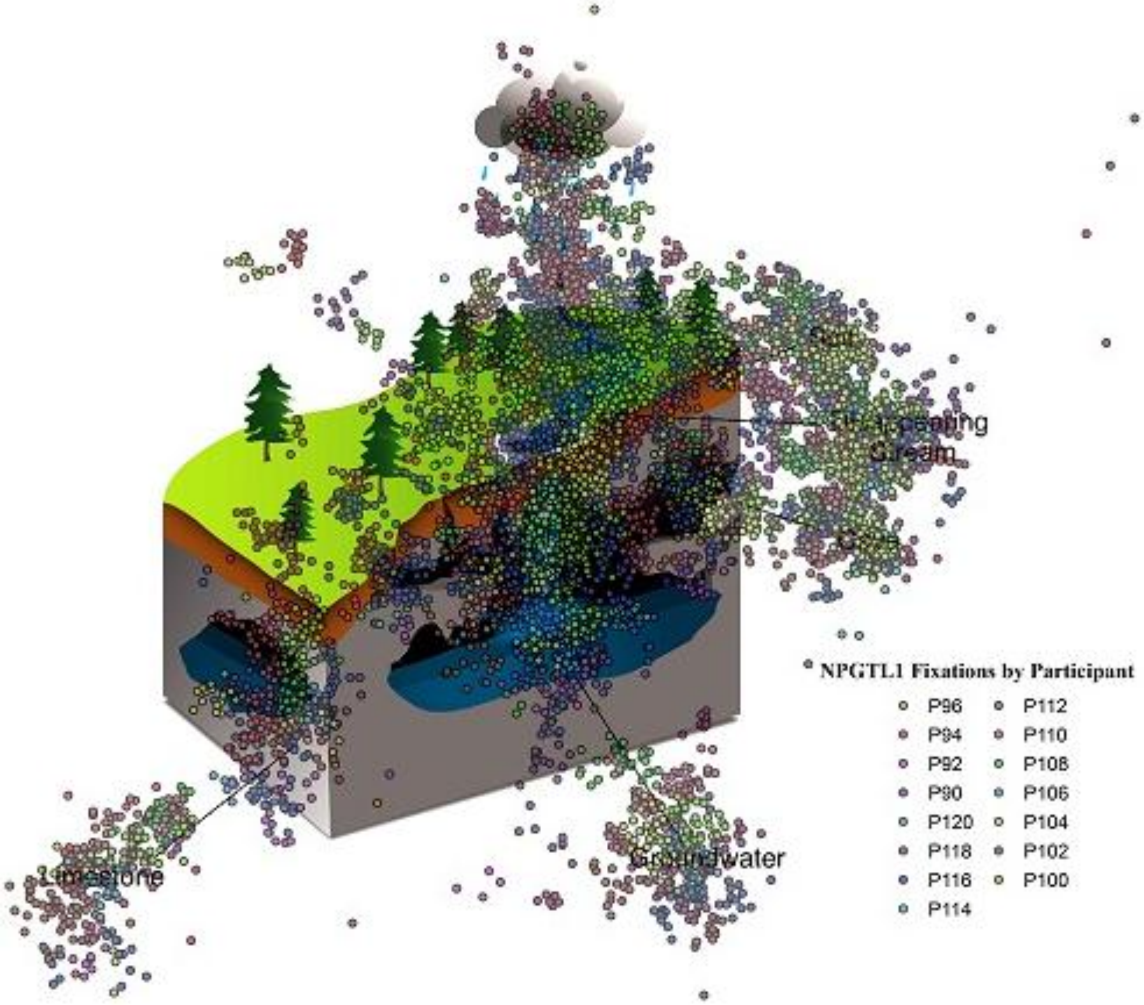


Figure 13. Raw fixation, equal interval gaze point coordinates plotted for all participants in NPGTL1

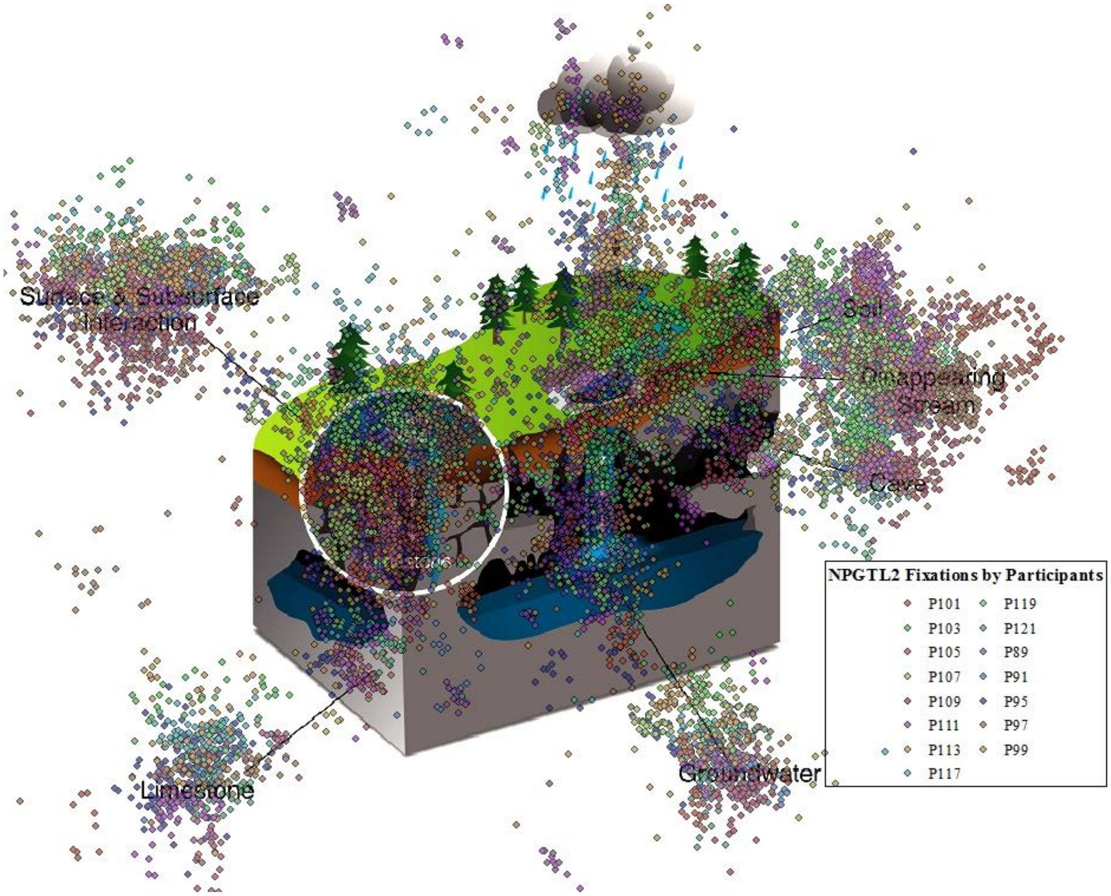


Figure 14. Raw fixation, equal interval gaze point coordinates plotted for all participants in NPGTL2

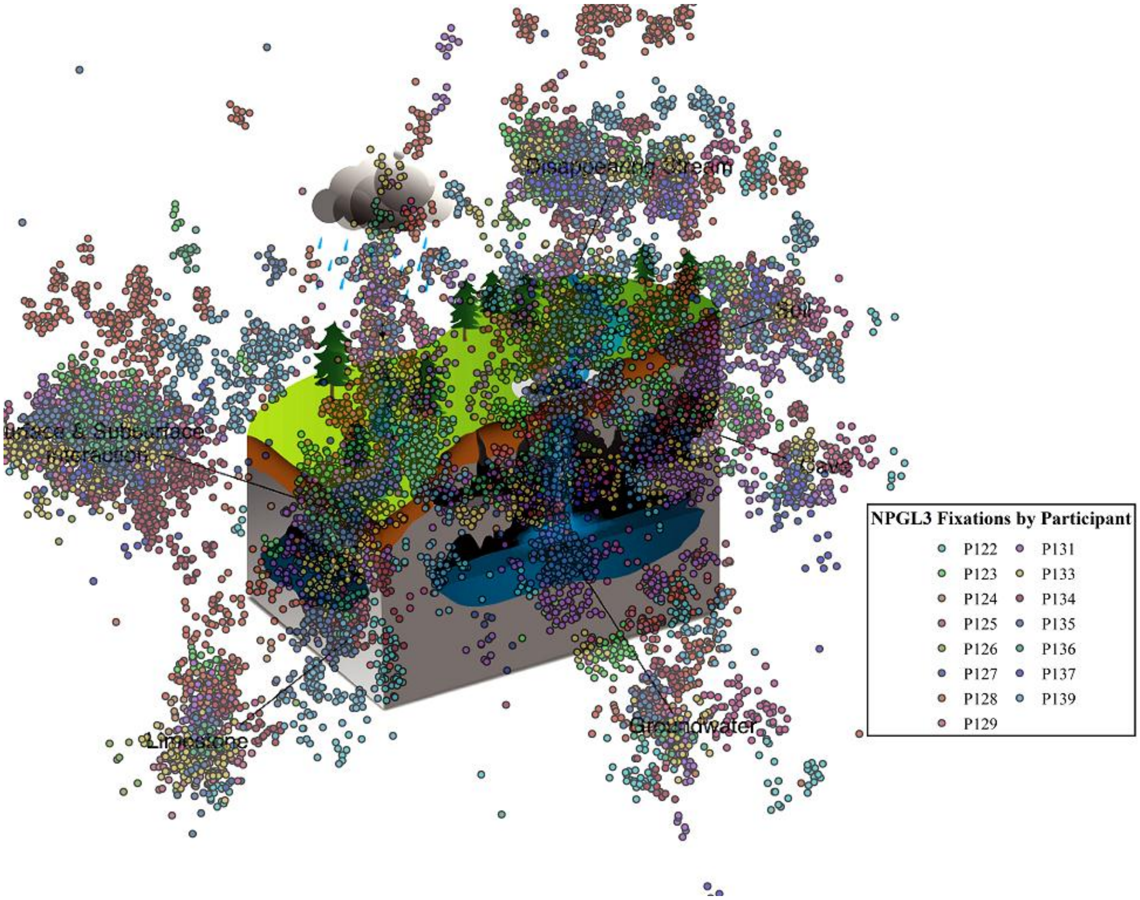


Figure 15. Raw fixation, equal interval gaze point coordinates plotted for all participants in NPGTL3

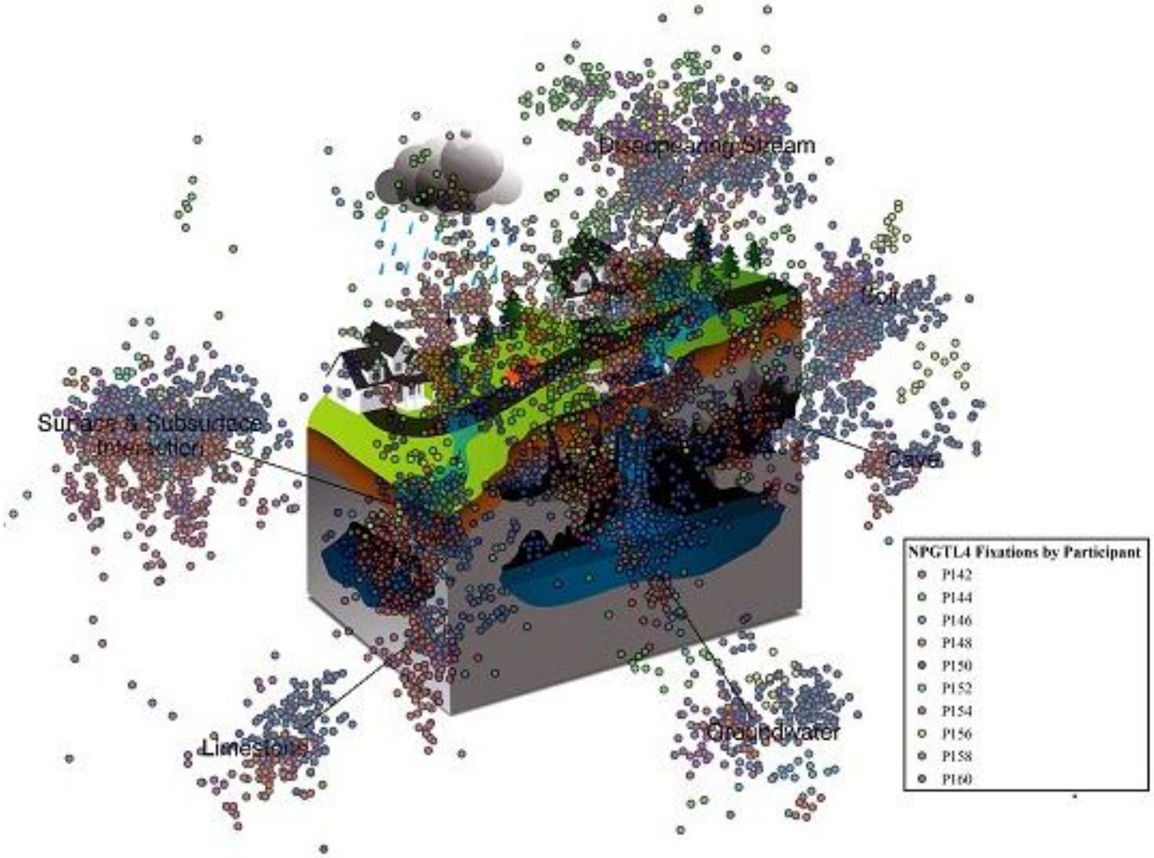


Figure 16. Raw fixation, equal interval gaze point coordinates plotted for all participants in NPGTL1

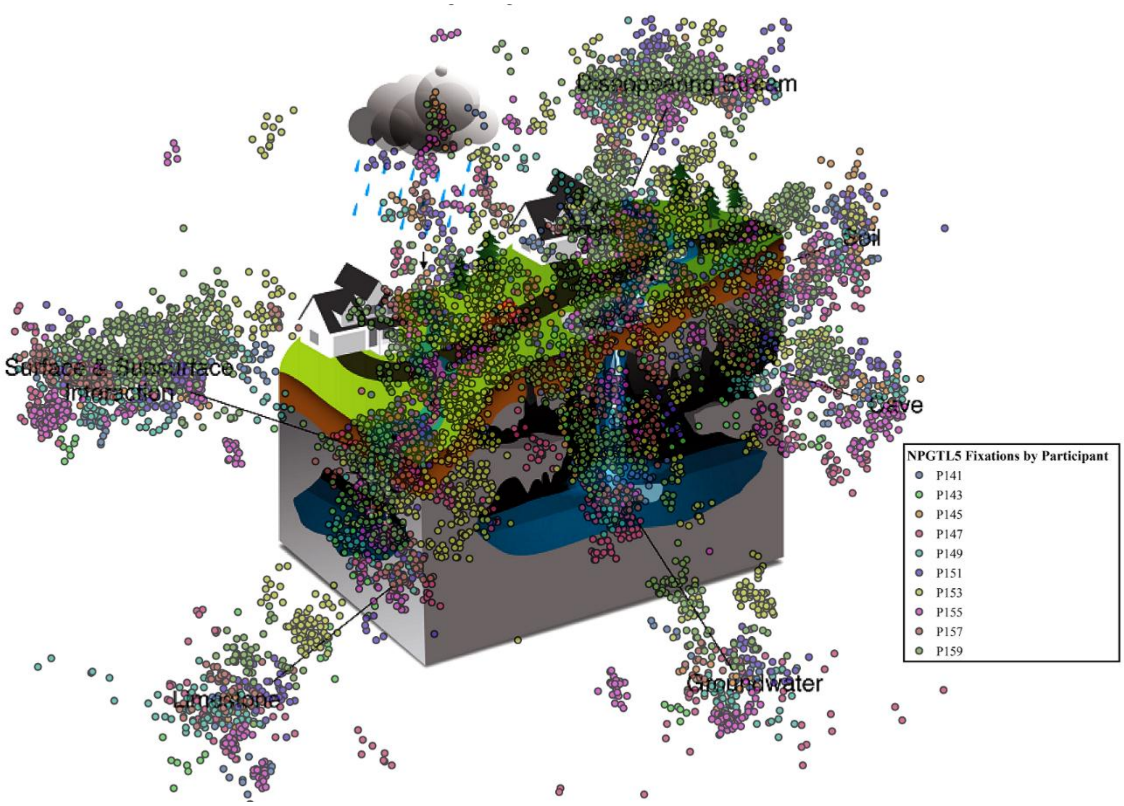
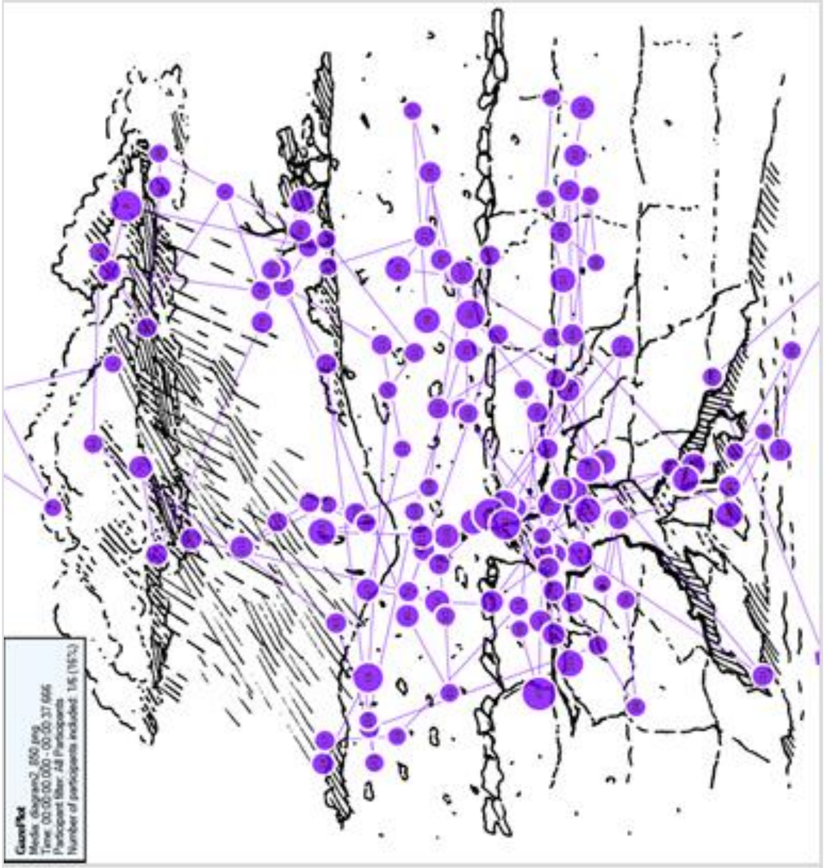
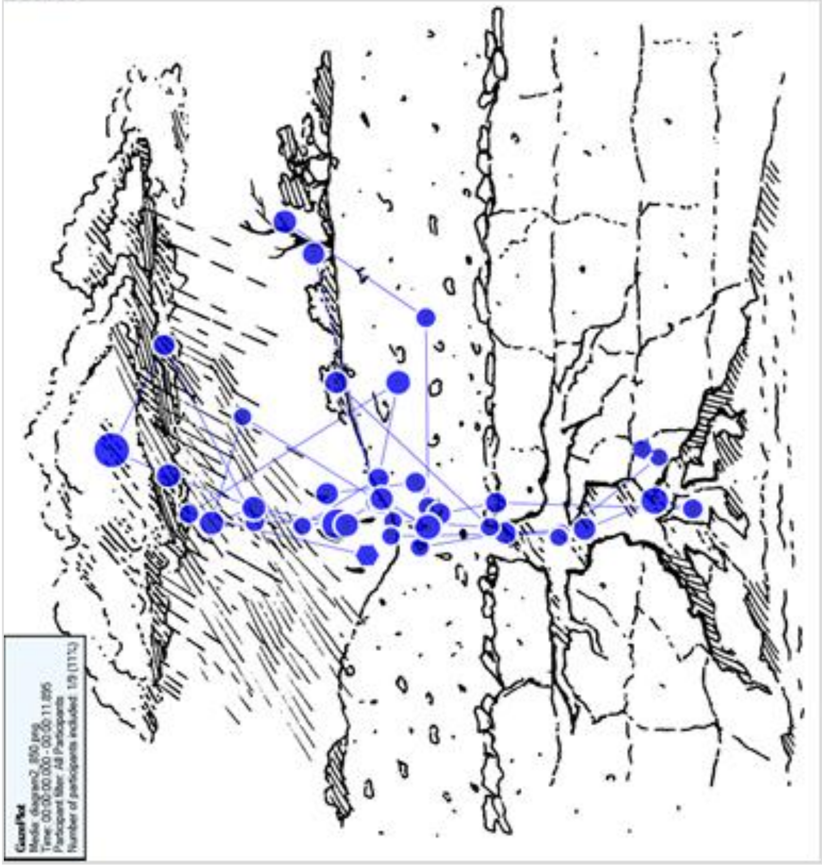


Figure 17. Raw fixation, equal interval gaze point coordinates plotted for all participants in NPGTL1


GazePlot
Media: diagram2_850.png
Time: 00:00:00.000 - 00:00:37.666
Participant filter: All Participants
Number of participants included: 1/6 (16%)

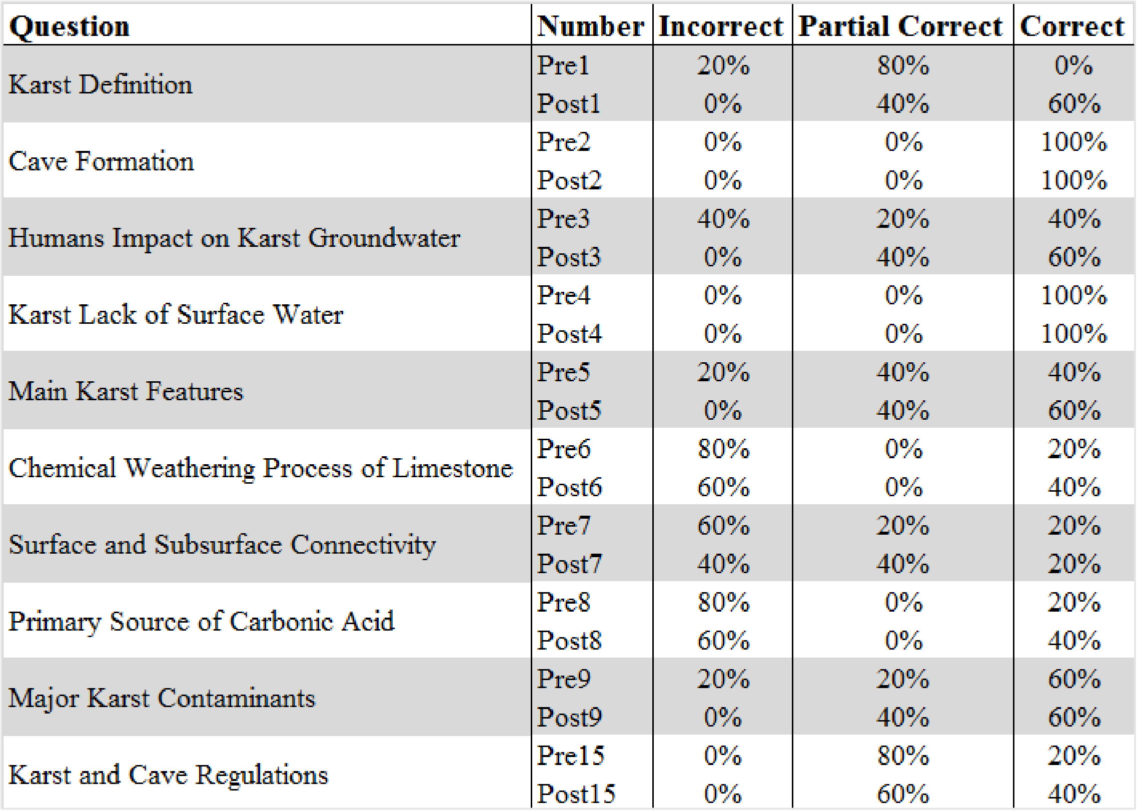

GazePlot
Media: diagram2_850.png
Time: 00:00:00.000 - 00:00:11.895
Participant filter: All Participants
Number of participants included: 1/9 (11%)

a) b)

Figure 18. Tobii Studio 3.2 gaze plots of a) prior-geoscience participant b) non-prior geoscience participant

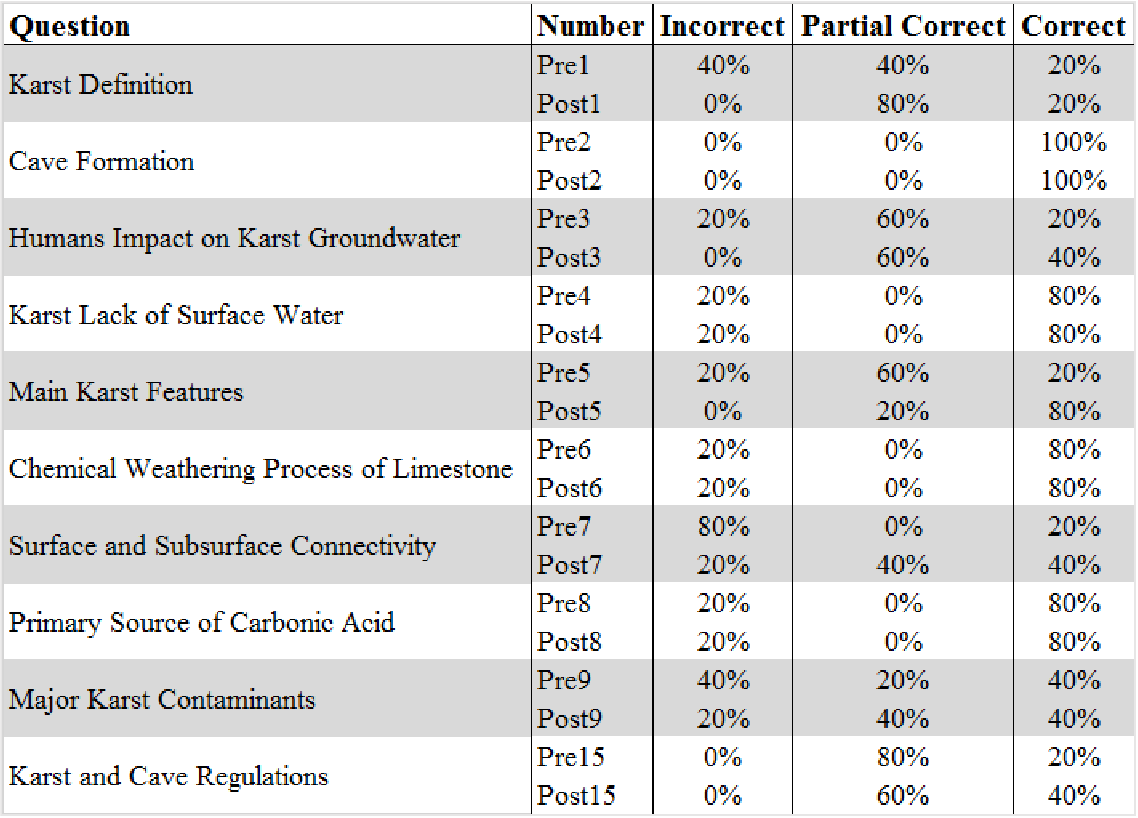
APPENDIX D: PRE- AND POST-ASSESSMENT TABLES PER TRIAL

Table 1. Pre- and post- assessment learning outcomes of NPGT1 participants (n=5)



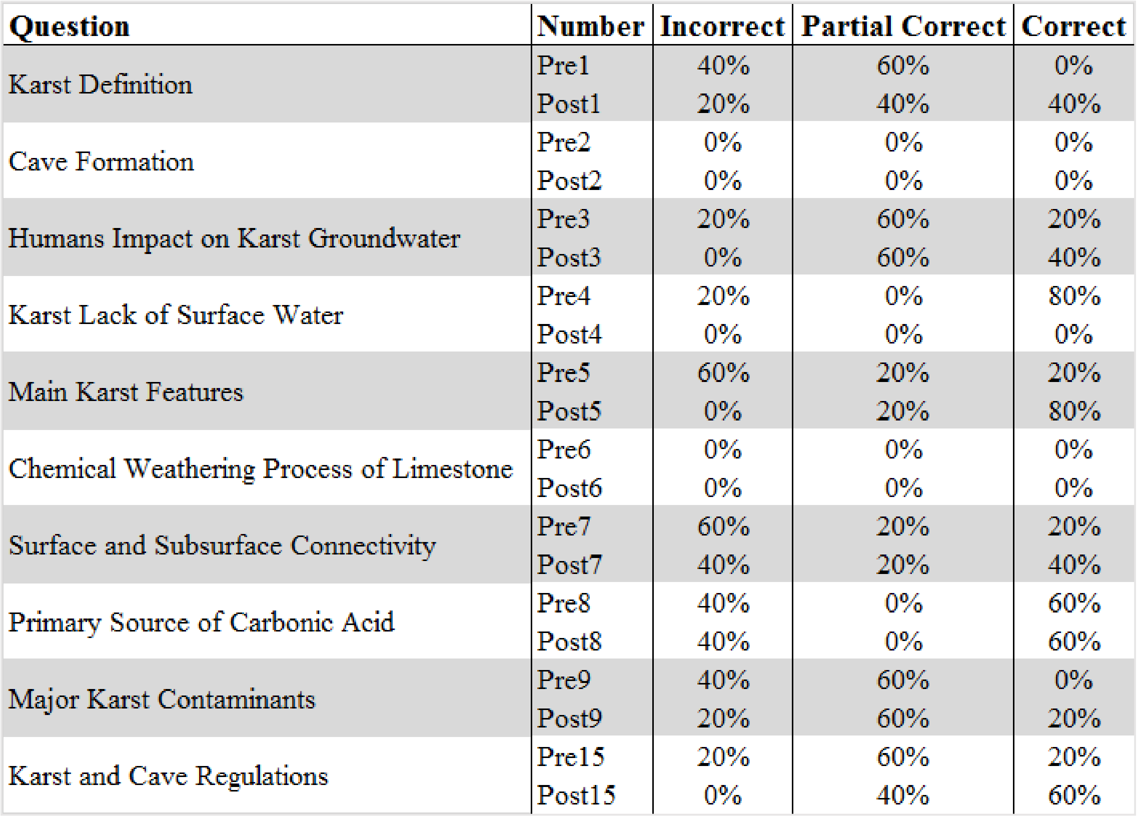
Question	Number	Incorrect	Partial Correct	Correct
Karst Definition	Pre1	20%	80%	0%
	Post1	0%	40%	60%
Cave Formation	Pre2	0%	0%	100%
	Post2	0%	0%	100%
Humans Impact on Karst Groundwater	Pre3	40%	20%	40%
	Post3	0%	40%	60%
Karst Lack of Surface Water	Pre4	0%	0%	100%
	Post4	0%	0%	100%
Main Karst Features	Pre5	20%	40%	40%
	Post5	0%	40%	60%
Chemical Weathering Process of Limestone	Pre6	80%	0%	20%
	Post6	60%	0%	40%
Surface and Subsurface Connectivity	Pre7	60%	20%	20%
	Post7	40%	40%	20%
Primary Source of Carbonic Acid	Pre8	80%	0%	20%
	Post8	60%	0%	40%
Major Karst Contaminants	Pre9	20%	20%	60%
	Post9	0%	40%	60%
Karst and Cave Regulations	Pre15	0%	80%	20%
	Post15	0%	60%	40%

Table 2. Pre- and post- assessment learning outcomes of NPGT2 participants (n=5)



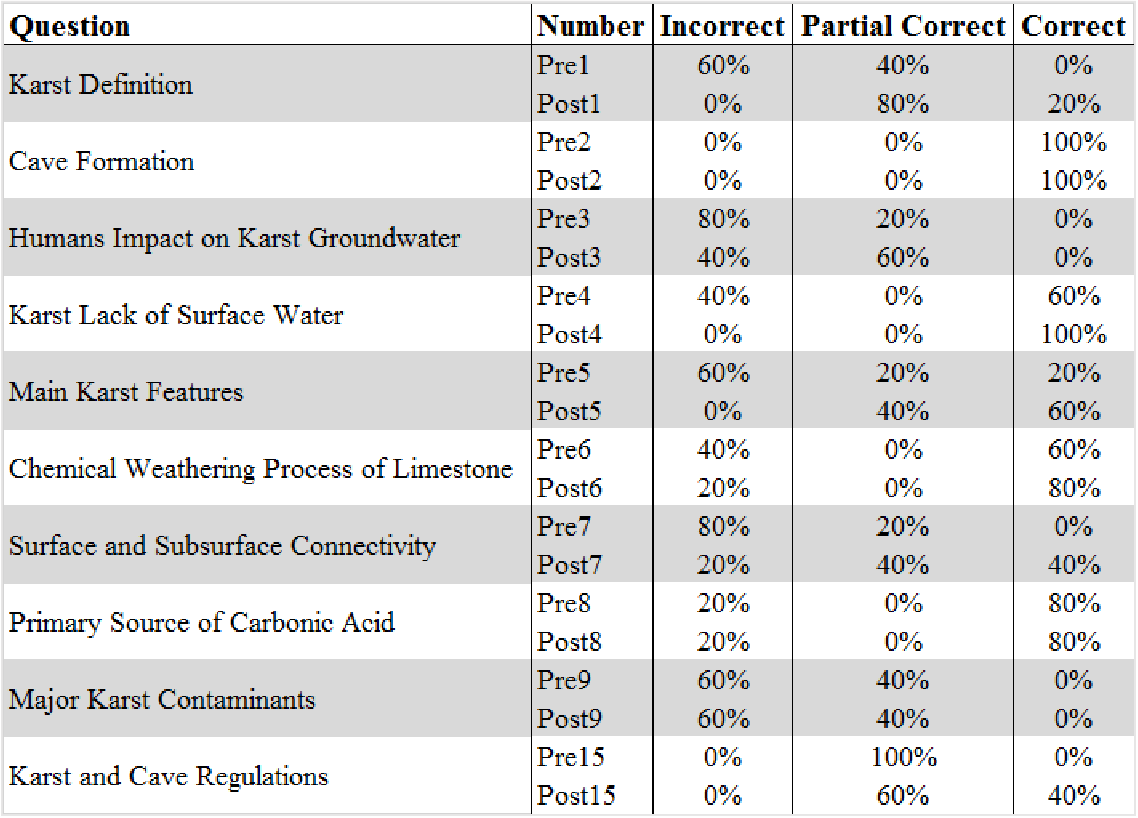
Question	Number	Incorrect	Partial Correct	Correct
Karst Definition	Pre1	40%	40%	20%
	Post1	0%	80%	20%
Cave Formation	Pre2	0%	0%	100%
	Post2	0%	0%	100%
Humans Impact on Karst Groundwater	Pre3	20%	60%	20%
	Post3	0%	60%	40%
Karst Lack of Surface Water	Pre4	20%	0%	80%
	Post4	20%	0%	80%
Main Karst Features	Pre5	20%	60%	20%
	Post5	0%	20%	80%
Chemical Weathering Process of Limestone	Pre6	20%	0%	80%
	Post6	20%	0%	80%
Surface and Subsurface Connectivity	Pre7	80%	0%	20%
	Post7	20%	40%	40%
Primary Source of Carbonic Acid	Pre8	20%	0%	80%
	Post8	20%	0%	80%
Major Karst Contaminants	Pre9	40%	20%	40%
	Post9	20%	40%	40%
Karst and Cave Regulations	Pre15	0%	80%	20%
	Post15	0%	60%	40%

Table 3. Pre- and post- assessment learning outcomes of NPGT3 participants (n=5)



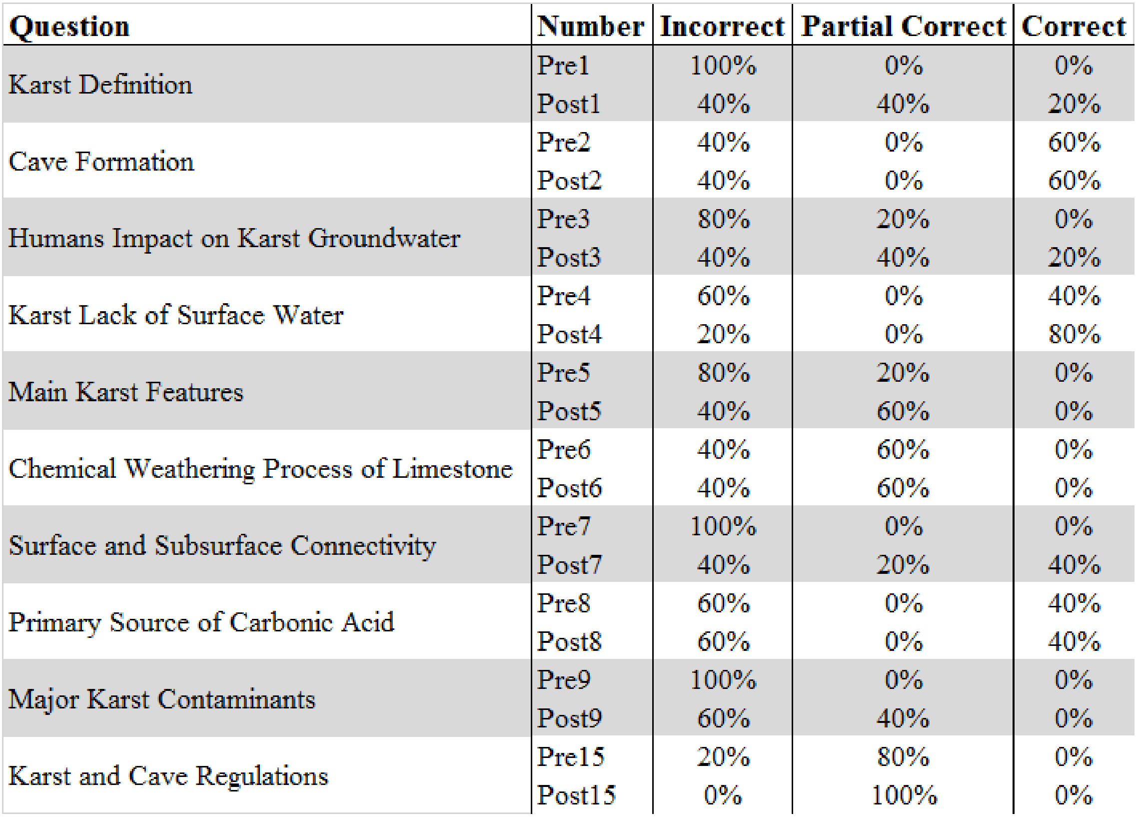
Question	**Number**	**Incorrect**	**Partial Correct**	**Correct**
Karst Definition	Pre1	40%	60%	0%
	Post1	20%	40%	40%
Cave Formation	Pre2	0%	0%	0%
	Post2	0%	0%	0%
Humans Impact on Karst Groundwater	Pre3	20%	60%	20%
	Post3	0%	60%	40%
Karst Lack of Surface Water	Pre4	20%	0%	80%
	Post4	0%	0%	0%
Main Karst Features	Pre5	60%	20%	20%
	Post5	0%	20%	80%
Chemical Weathering Process of Limestone	Pre6	0%	0%	0%
	Post6	0%	0%	0%
Surface and Subsurface Connectivity	Pre7	60%	20%	20%
	Post7	40%	20%	40%
Primary Source of Carbonic Acid	Pre8	40%	0%	60%
	Post8	40%	0%	60%
Major Karst Contaminants	Pre9	40%	60%	0%
	Post9	20%	60%	20%
Karst and Cave Regulations	Pre15	20%	60%	20%
	Post15	0%	40%	60%

Table 4. Pre- and post- assessment learning outcomes of NPGT4 participants (n=5)



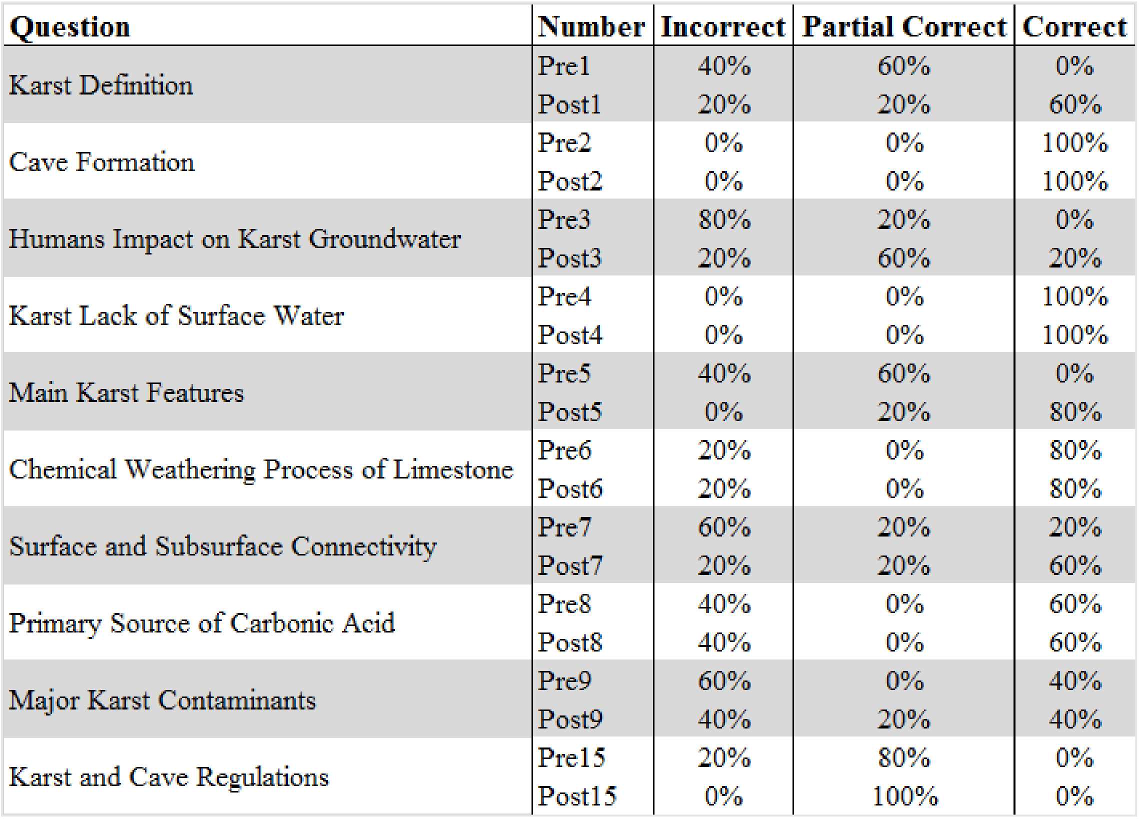
Question	**Number**	**Incorrect**	**Partial Correct**	**Correct**
Karst Definition	Pre1	60%	40%	0%
	Post1	0%	80%	20%
Cave Formation	Pre2	0%	0%	100%
	Post2	0%	0%	100%
Humans Impact on Karst Groundwater	Pre3	80%	20%	0%
	Post3	40%	60%	0%
Karst Lack of Surface Water	Pre4	40%	0%	60%
	Post4	0%	0%	100%
Main Karst Features	Pre5	60%	20%	20%
	Post5	0%	40%	60%
Chemical Weathering Process of Limestone	Pre6	40%	0%	60%
	Post6	20%	0%	80%
Surface and Subsurface Connectivity	Pre7	80%	20%	0%
	Post7	20%	40%	40%
Primary Source of Carbonic Acid	Pre8	20%	0%	80%
	Post8	20%	0%	80%
Major Karst Contaminants	Pre9	60%	40%	0%
	Post9	60%	40%	0%
Karst and Cave Regulations	Pre15	0%	100%	0%
	Post15	0%	60%	40%

Table 5. Pre- and post- assessment learning outcomes of NPGT5 participants (n=5)



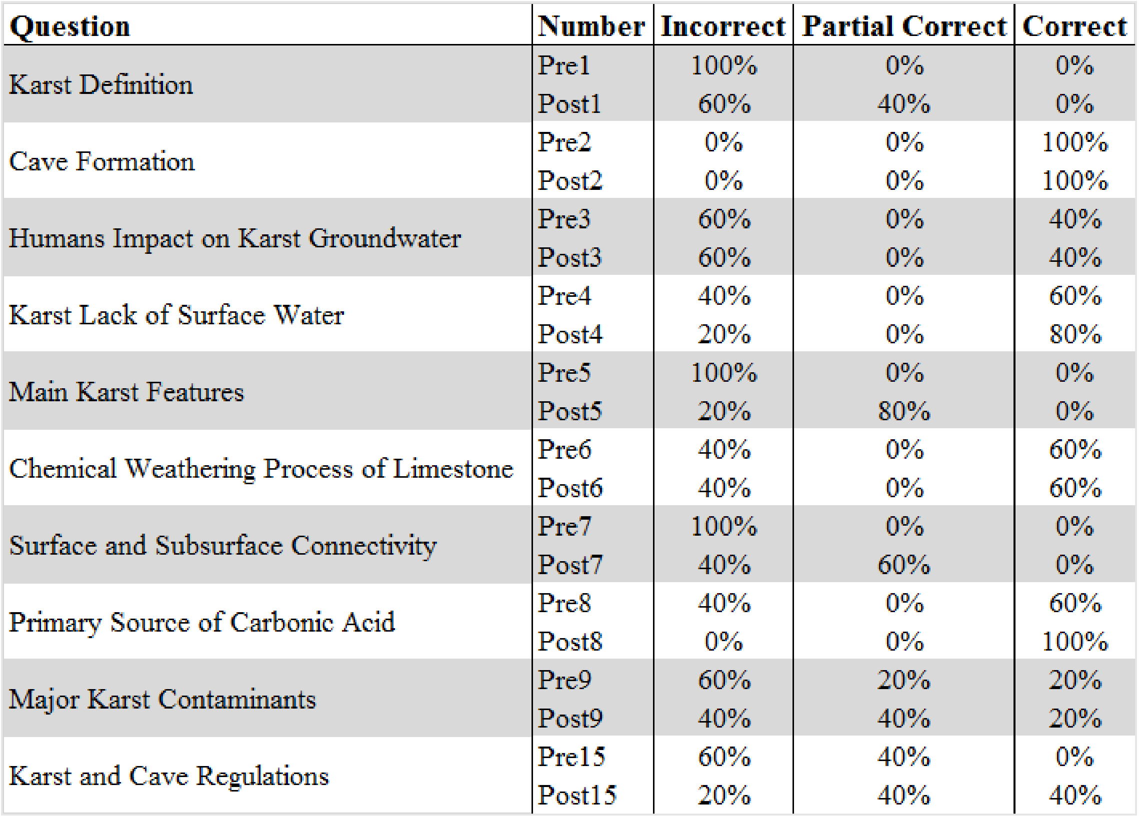
Question	Number	Incorrect	Partial Correct	Correct
Karst Definition	Pre1	100%	0%	0%
	Post1	40%	40%	20%
Cave Formation	Pre2	40%	0%	60%
	Post2	40%	0%	60%
Humans Impact on Karst Groundwater	Pre3	80%	20%	0%
	Post3	40%	40%	20%
Karst Lack of Surface Water	Pre4	60%	0%	40%
	Post4	20%	0%	80%
Main Karst Features	Pre5	80%	20%	0%
	Post5	40%	60%	0%
Chemical Weathering Process of Limestone	Pre6	40%	60%	0%
	Post6	40%	60%	0%
Surface and Subsurface Connectivity	Pre7	100%	0%	0%
	Post7	40%	20%	40%
Primary Source of Carbonic Acid	Pre8	60%	0%	40%
	Post8	60%	0%	40%
Major Karst Contaminants	Pre9	100%	0%	0%
	Post9	60%	40%	0%
Karst and Cave Regulations	Pre15	20%	80%	0%
	Post15	0%	100%	0%

Table 6. Pre- and post- assessment learning outcomes of NPGT6 participants (n=5)



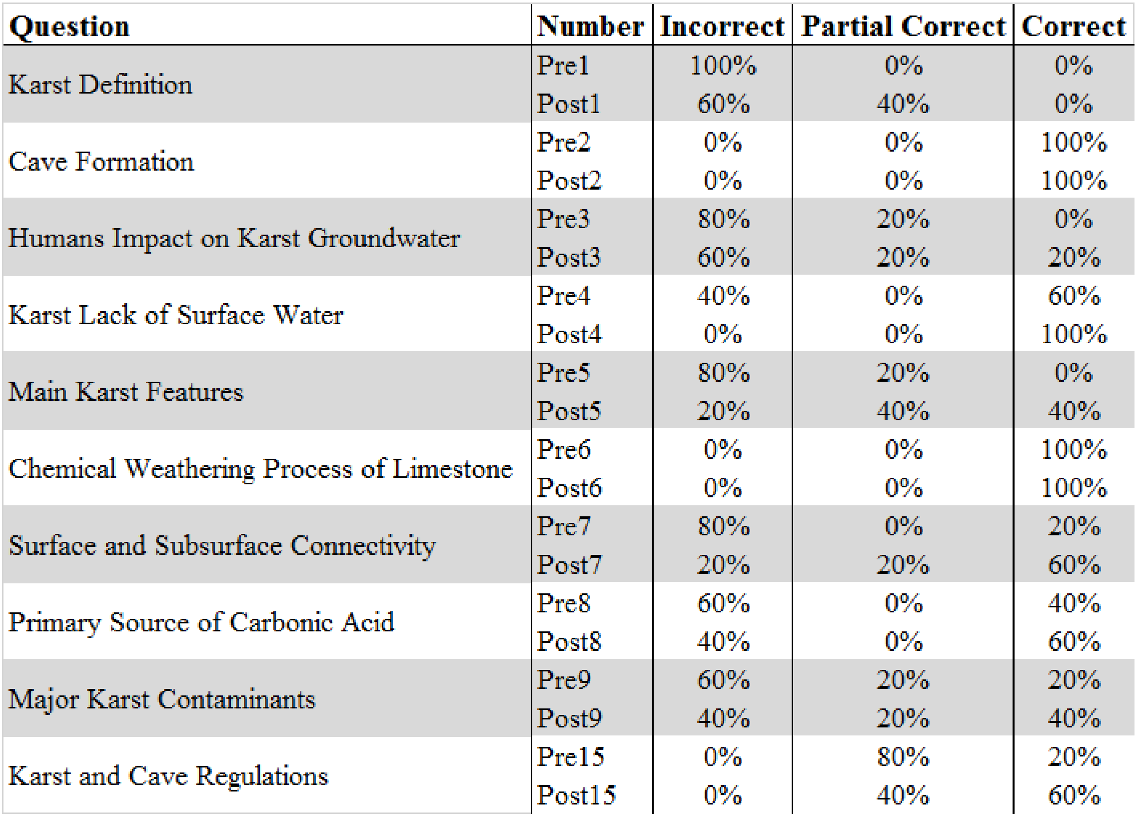
Question	Number	Incorrect	Partial Correct	Correct
Karst Definition	Pre1	40%	60%	0%
	Post1	20%	20%	60%
Cave Formation	Pre2	0%	0%	100%
	Post2	0%	0%	100%
Humans Impact on Karst Groundwater	Pre3	80%	20%	0%
	Post3	20%	60%	20%
Karst Lack of Surface Water	Pre4	0%	0%	100%
	Post4	0%	0%	100%
Main Karst Features	Pre5	40%	60%	0%
	Post5	0%	20%	80%
Chemical Weathering Process of Limestone	Pre6	20%	0%	80%
	Post6	20%	0%	80%
Surface and Subsurface Connectivity	Pre7	60%	20%	20%
	Post7	20%	20%	60%
Primary Source of Carbonic Acid	Pre8	40%	0%	60%
	Post8	40%	0%	60%
Major Karst Contaminants	Pre9	60%	0%	40%
	Post9	40%	20%	40%
Karst and Cave Regulations	Pre15	20%	80%	0%
	Post15	0%	100%	0%

Table 7. Pre- and post- assessment learning outcomes of NPGT7 participants (n=5)



Question	Number	Incorrect	Partial Correct	Correct
Karst Definition	Pre1	100%	0%	0%
	Post1	60%	40%	0%
Cave Formation	Pre2	0%	0%	100%
	Post2	0%	0%	100%
Humans Impact on Karst Groundwater	Pre3	60%	0%	40%
	Post3	60%	0%	40%
Karst Lack of Surface Water	Pre4	40%	0%	60%
	Post4	20%	0%	80%
Main Karst Features	Pre5	100%	0%	0%
	Post5	20%	80%	0%
Chemical Weathering Process of Limestone	Pre6	40%	0%	60%
	Post6	40%	0%	60%
Surface and Subsurface Connectivity	Pre7	100%	0%	0%
	Post7	40%	60%	0%
Primary Source of Carbonic Acid	Pre8	40%	0%	60%
	Post8	0%	0%	100%
Major Karst Contaminants	Pre9	60%	20%	20%
	Post9	40%	40%	20%
Karst and Cave Regulations	Pre15	60%	40%	0%
	Post15	20%	40%	40%

Table 8. Pre- and post- assessment learning outcomes of NPGT8 participants (n=5)

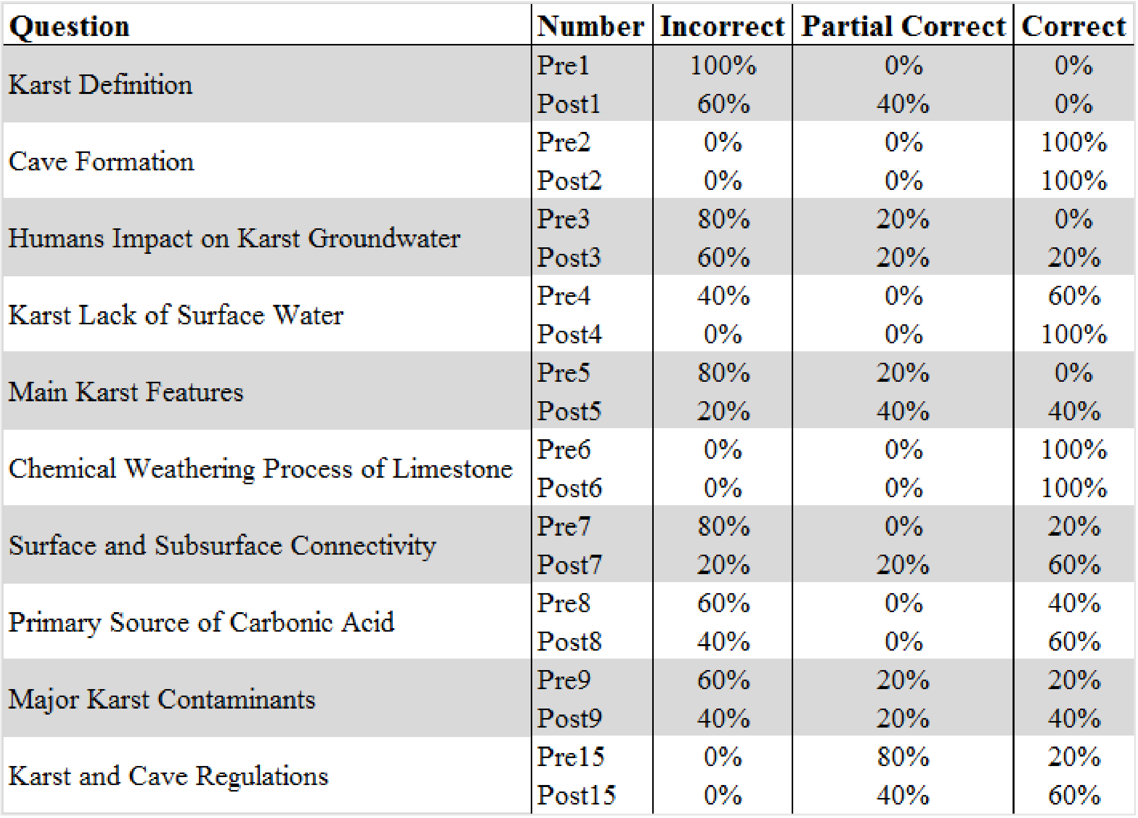


Question	Number	Incorrect	Partial Correct	Correct
Karst Definition	Pre1	100%	0%	0%
	Post1	60%	40%	0%
Cave Formation	Pre2	0%	0%	100%
	Post2	0%	0%	100%
Humans Impact on Karst Groundwater	Pre3	80%	20%	0%
	Post3	60%	20%	20%
Karst Lack of Surface Water	Pre4	40%	0%	60%
	Post4	0%	0%	100%
Main Karst Features	Pre5	80%	20%	0%
	Post5	20%	40%	40%
Chemical Weathering Process of Limestone	Pre6	0%	0%	100%
	Post6	0%	0%	100%
Surface and Subsurface Connectivity	Pre7	80%	0%	20%
	Post7	20%	20%	60%
Primary Source of Carbonic Acid	Pre8	60%	0%	40%
	Post8	40%	0%	60%
Major Karst Contaminants	Pre9	60%	20%	20%
	Post9	40%	20%	40%
Karst and Cave Regulations	Pre15	0%	80%	20%
	Post15	0%	40%	60%

Table 9. Pre- and post- assessment learning outcomes of NPGT9 participants (n=5)

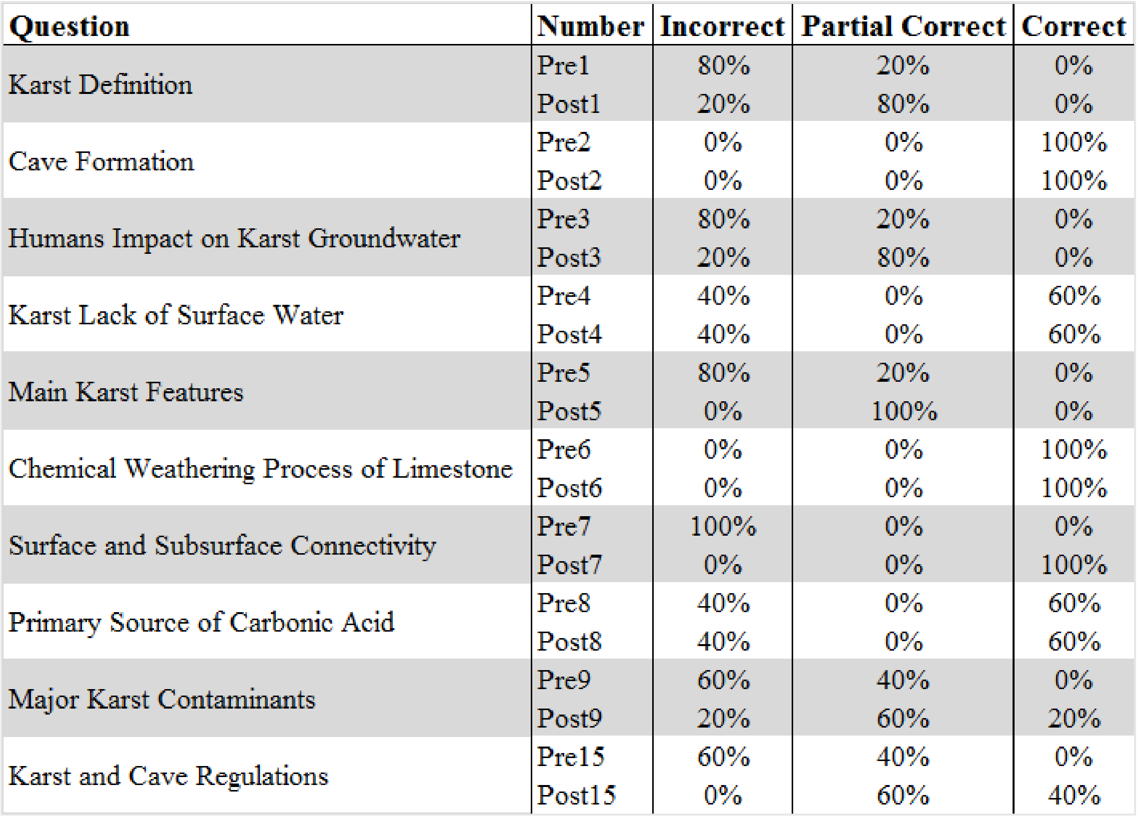
Question	Number	Incorrect	Partial Correct	Correct
Karst Definition	Pre1	100%	0%	0%
	Post1	20%	60%	20%
Cave Formation	Pre2	0%	0%	100%
	Post2	0%	0%	100%
Humans Impact on Karst Groundwater	Pre3	60%	40%	0%
	Post3	60%	40%	0%
Karst Lack of Surface Water	Pre4	20%	0%	80%
	Post4	20%	0%	80%
Main Karst Features	Pre5	60%	40%	0%
	Post5	0%	60%	40%
Chemical Weathering Process of Limestone	Pre6	60%	0%	40%
	Post6	40%	0%	60%
Surface and Subsurface Connectivity	Pre7	100%	0%	0%
	Post7	0%	60%	40%
Primary Source of Carbonic Acid	Pre8	60%	0%	40%
	Post8	60%	0%	40%
Major Karst Contaminants	Pre9	60%	20%	20%
	Post9	60%	20%	20%
Karst and Cave Regulations	Pre15	20%	40%	40%
	Post15	20%	20%	60%

Table 10. Pre- and post- assessment learning outcomes of NPGT10 participants (n=5)



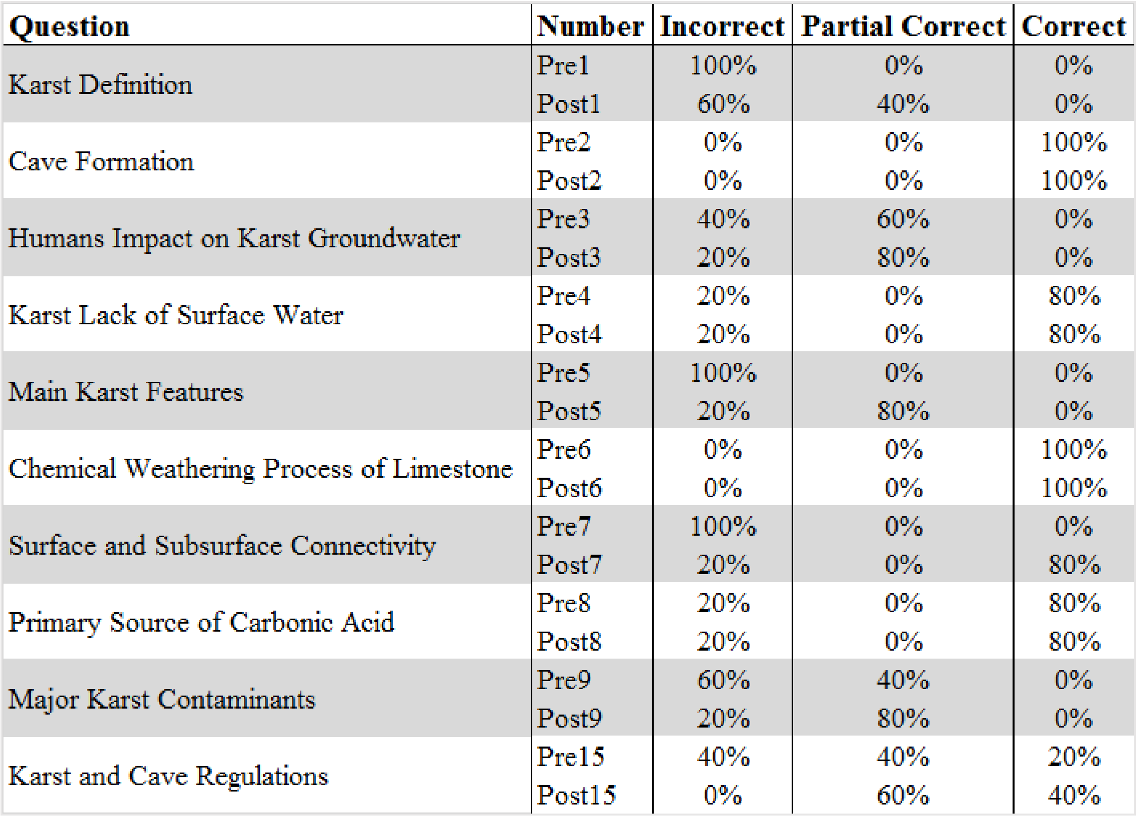
Question	Number	Incorrect	Partial Correct	Correct
Karst Definition	Pre1	100%	0%	0%
	Post1	60%	40%	0%
Cave Formation	Pre2	0%	0%	100%
	Post2	0%	0%	100%
Humans Impact on Karst Groundwater	Pre3	80%	20%	0%
	Post3	60%	20%	20%
Karst Lack of Surface Water	Pre4	40%	0%	60%
	Post4	0%	0%	100%
Main Karst Features	Pre5	80%	20%	0%
	Post5	20%	40%	40%
Chemical Weathering Process of Limestone	Pre6	0%	0%	100%
	Post6	0%	0%	100%
Surface and Subsurface Connectivity	Pre7	80%	0%	20%
	Post7	20%	20%	60%
Primary Source of Carbonic Acid	Pre8	60%	0%	40%
	Post8	40%	0%	60%
Major Karst Contaminants	Pre9	60%	20%	20%
	Post9	40%	20%	40%
Karst and Cave Regulations	Pre15	0%	80%	20%
	Post15	0%	40%	60%

Table 11. Pre- and post- assessment learning outcomes of NPGT11 participants (n=5)



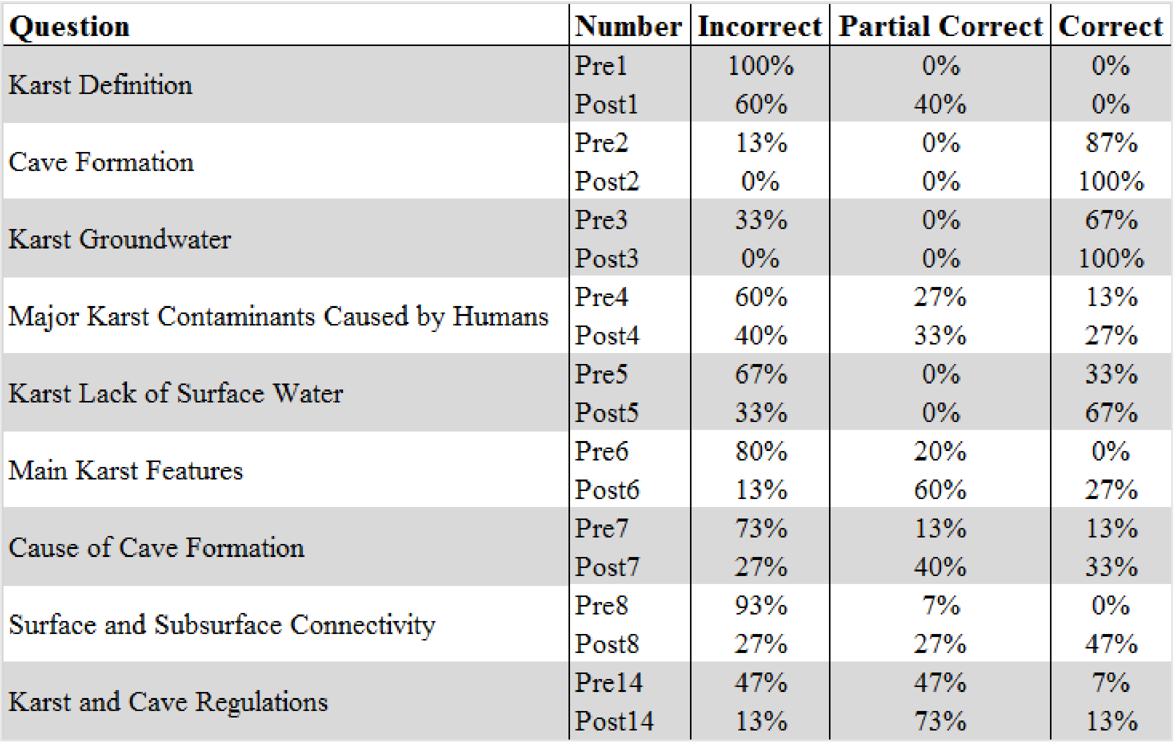
Question	Number	Incorrect	Partial Correct	Correct
Karst Definition	Pre1	80%	20%	0%
	Post1	20%	80%	0%
Cave Formation	Pre2	0%	0%	100%
	Post2	0%	0%	100%
Humans Impact on Karst Groundwater	Pre3	80%	20%	0%
	Post3	20%	80%	0%
Karst Lack of Surface Water	Pre4	40%	0%	60%
	Post4	40%	0%	60%
Main Karst Features	Pre5	80%	20%	0%
	Post5	0%	100%	0%
Chemical Weathering Process of Limestone	Pre6	0%	0%	100%
	Post6	0%	0%	100%
Surface and Subsurface Connectivity	Pre7	100%	0%	0%
	Post7	0%	0%	100%
Primary Source of Carbonic Acid	Pre8	40%	0%	60%
	Post8	40%	0%	60%
Major Karst Contaminants	Pre9	60%	40%	0%
	Post9	20%	60%	20%
Karst and Cave Regulations	Pre15	60%	40%	0%
	Post15	0%	60%	40%

Table 12. Pre- and post- assessment learning outcomes of NPGT12 participants (n=5)



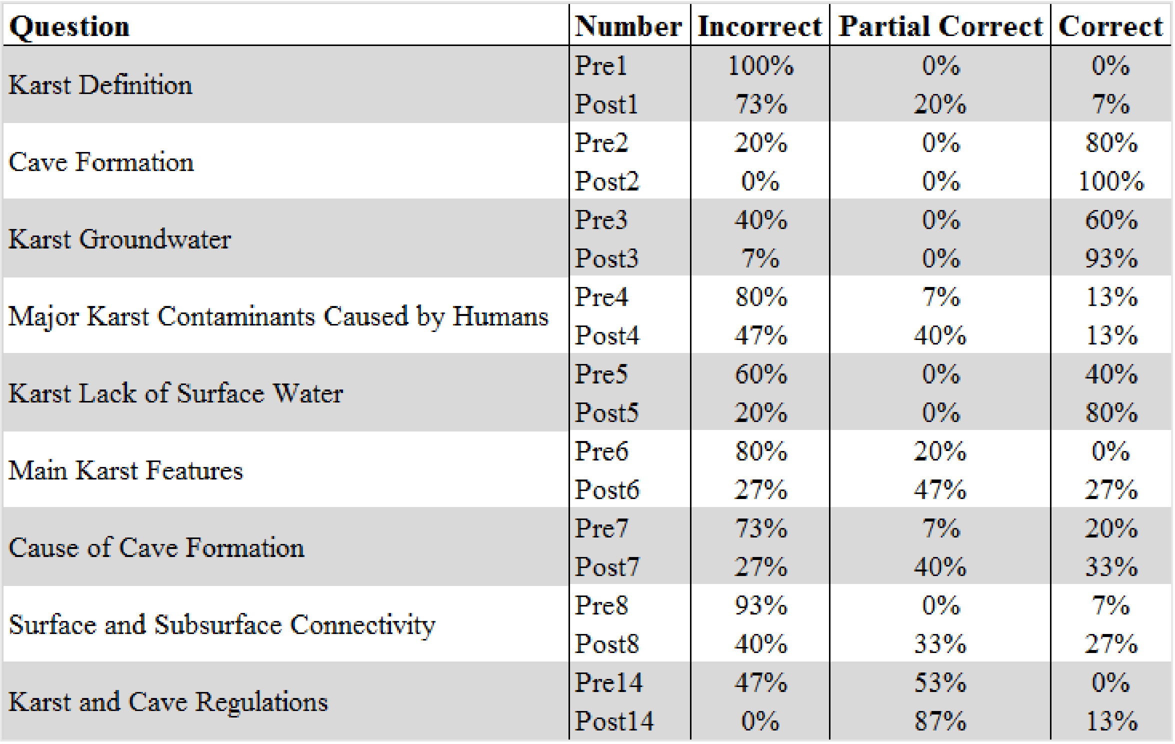
Question	Number	Incorrect	Partial Correct	Correct
Karst Definition	Pre1	100%	0%	0%
	Post1	60%	40%	0%
Cave Formation	Pre2	0%	0%	100%
	Post2	0%	0%	100%
Humans Impact on Karst Groundwater	Pre3	40%	60%	0%
	Post3	20%	80%	0%
Karst Lack of Surface Water	Pre4	20%	0%	80%
	Post4	20%	0%	80%
Main Karst Features	Pre5	100%	0%	0%
	Post5	20%	80%	0%
Chemical Weathering Process of Limestone	Pre6	0%	0%	100%
	Post6	0%	0%	100%
Surface and Subsurface Connectivity	Pre7	100%	0%	0%
	Post7	20%	0%	80%
Primary Source of Carbonic Acid	Pre8	20%	0%	80%
	Post8	20%	0%	80%
Major Karst Contaminants	Pre9	60%	40%	0%
	Post9	20%	80%	0%
Karst and Cave Regulations	Pre15	40%	40%	20%
	Post15	0%	60%	40%

Table 13. Pre- and post- assessment learning outcomes of NPGTL1 participants (n=15)



Question	**Number**	**Incorrect**	**Partial Correct**	**Correct**
Karst Definition	Pre1	100%	0%	0%
	Post1	60%	40%	0%
Cave Formation	Pre2	13%	0%	87%
	Post2	0%	0%	100%
Karst Groundwater	Pre3	33%	0%	67%
	Post3	0%	0%	100%
Major Karst Contaminants Caused by Humans	Pre4	60%	27%	13%
	Post4	40%	33%	27%
Karst Lack of Surface Water	Pre5	67%	0%	33%
	Post5	33%	0%	67%
Main Karst Features	Pre6	80%	20%	0%
	Post6	13%	60%	27%
Cause of Cave Formation	Pre7	73%	13%	13%
	Post7	27%	40%	33%
Surface and Subsurface Connectivity	Pre8	93%	7%	0%
	Post8	27%	27%	47%
Karst and Cave Regulations	Pre14	47%	47%	7%
	Post14	13%	73%	13%

Table 14. Pre- and post- assessment learning outcomes of NPGTL2 participants (n=15)

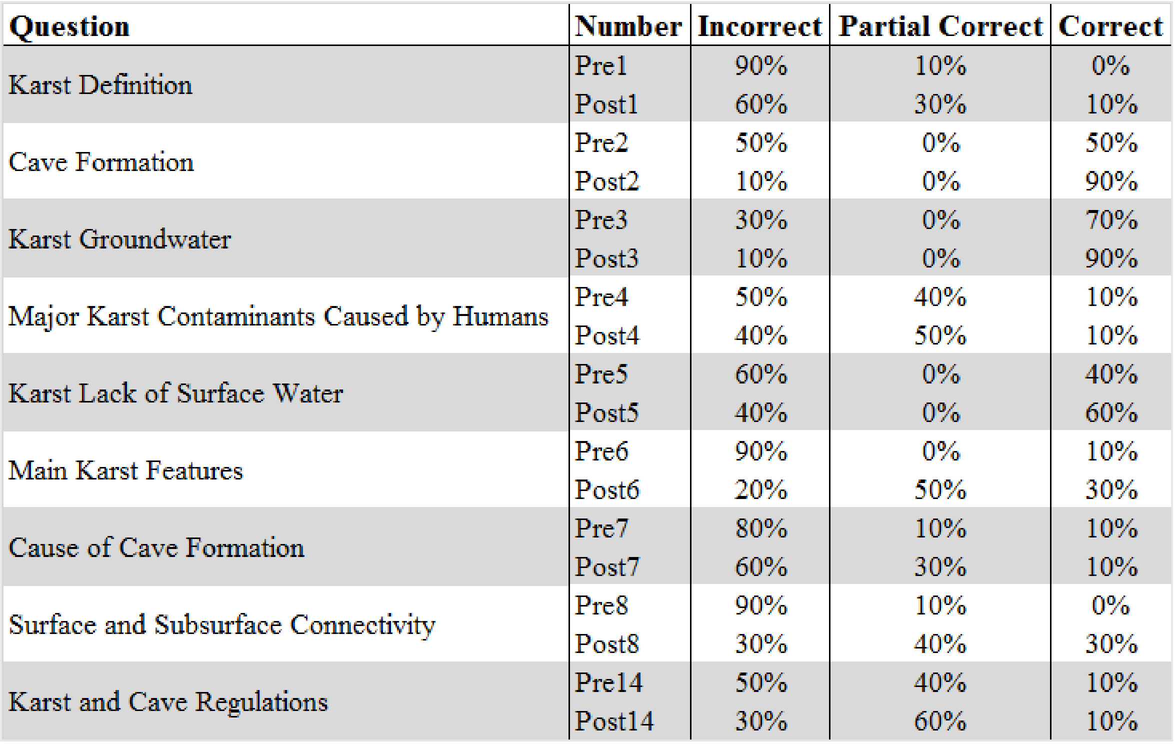


Question	**Number**	**Incorrect**	**Partial Correct**	**Correct**
Karst Definition	Pre1	100%	0%	0%
	Post1	73%	20%	7%
Cave Formation	Pre2	20%	0%	80%
	Post2	0%	0%	100%
Karst Groundwater	Pre3	40%	0%	60%
	Post3	7%	0%	93%
Major Karst Contaminants Caused by Humans	Pre4	80%	7%	13%
	Post4	47%	40%	13%
Karst Lack of Surface Water	Pre5	60%	0%	40%
	Post5	20%	0%	80%
Main Karst Features	Pre6	80%	20%	0%
	Post6	27%	47%	27%
Cause of Cave Formation	Pre7	73%	7%	20%
	Post7	27%	40%	33%
Surface and Subsurface Connectivity	Pre8	93%	0%	7%
	Post8	40%	33%	27%
Karst and Cave Regulations	Pre14	47%	53%	0%
	Post14	0%	87%	13%

Table 15. Pre- and post- assessment learning outcomes of NPGTL3 participants (n=15)

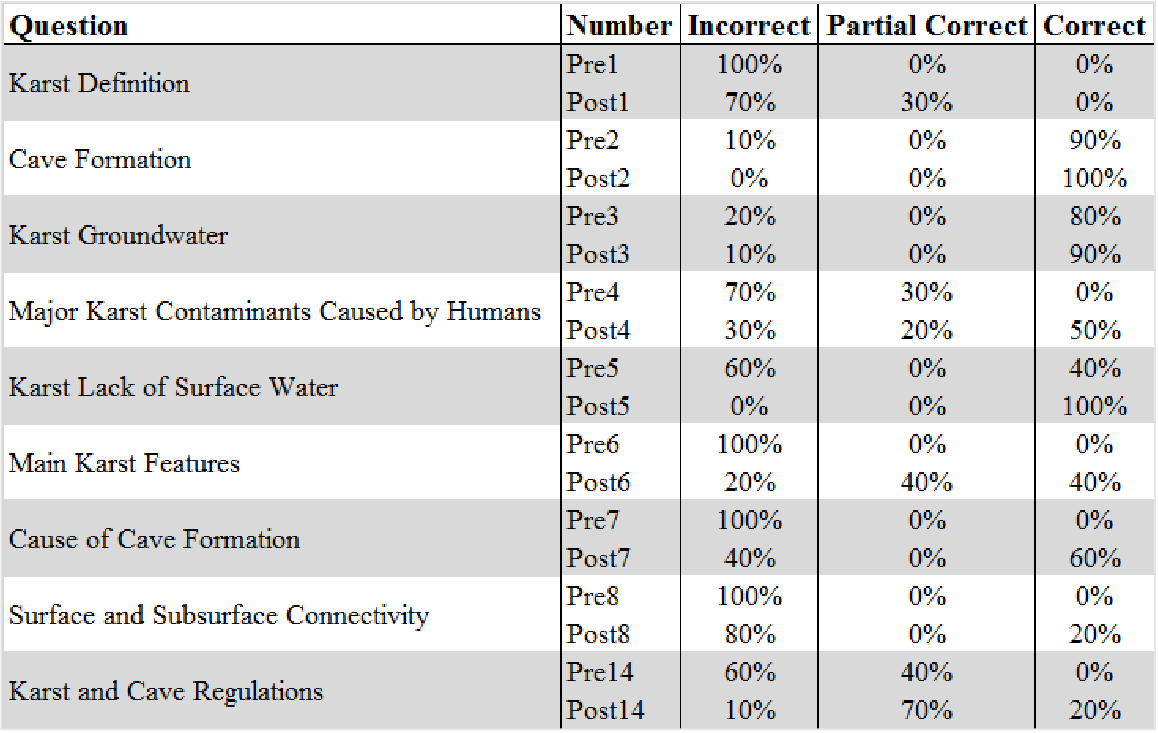
Question	Number	Incorrect	Partial Correct	Correct
Karst Definition	Pre1	87%	13%	0%
	Post1	40%	47%	13%
Cave Formation	Pre2	20%	0%	80%
	Post2	13%	0%	87%
Karst Groundwater	Pre3	13%	0%	87%
	Post3	0%	0%	100%
Major Karst Contaminants Caused by Humans	Pre4	60%	27%	13%
	Post4	33%	20%	47%
Karst Lack of Surface Water	Pre5	53%	0%	47%
	Post5	33%	0%	67%
Main Karst Features	Pre6	87%	13%	0%
	Post6	47%	0%	53%
Cause of Cave Formation	Pre7	67%	7%	27%
	Post7	33%	40%	27%
Surface and Subsurface Connectivity	Pre8	93%	7%	0%
	Post8	20%	20%	60%
Karst and Cave Regulations	Pre14	33%	67%	0%
	Post14	27%	33%	40%

Table 16. Pre- and post- assessment learning outcomes of NPGTL4 participants (n=10)



Question	Number	Incorrect	Partial Correct	Correct
Karst Definition	Pre1	90%	10%	0%
	Post1	60%	30%	10%
Cave Formation	Pre2	50%	0%	50%
	Post2	10%	0%	90%
Karst Groundwater	Pre3	30%	0%	70%
	Post3	10%	0%	90%
Major Karst Contaminants Caused by Humans	Pre4	50%	40%	10%
	Post4	40%	50%	10%
Karst Lack of Surface Water	Pre5	60%	0%	40%
	Post5	40%	0%	60%
Main Karst Features	Pre6	90%	0%	10%
	Post6	20%	50%	30%
Cause of Cave Formation	Pre7	80%	10%	10%
	Post7	60%	30%	10%
Surface and Subsurface Connectivity	Pre8	90%	10%	0%
	Post8	30%	40%	30%
Karst and Cave Regulations	Pre14	50%	40%	10%
	Post14	30%	60%	10%

Table 17. Pre- and post- assessment learning outcomes of NPGTL5 participants (n=10)



Question	Number	Incorrect	Partial Correct	Correct
Karst Definition	Pre1	100%	0%	0%
	Post1	70%	30%	0%
Cave Formation	Pre2	10%	0%	90%
	Post2	0%	0%	100%
Karst Groundwater	Pre3	20%	0%	80%
	Post3	10%	0%	90%
Major Karst Contaminants Caused by Humans	Pre4	70%	30%	0%
	Post4	30%	20%	50%
Karst Lack of Surface Water	Pre5	60%	0%	40%
	Post5	0%	0%	100%
Main Karst Features	Pre6	100%	0%	0%
	Post6	20%	40%	40%
Cause of Cave Formation	Pre7	100%	0%	0%
	Post7	40%	0%	60%
Surface and Subsurface Connectivity	Pre8	100%	0%	0%
	Post8	80%	0%	20%
Karst and Cave Regulations	Pre14	60%	40%	0%
	Post14	10%	70%	20%

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