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Geospatial Image Browsing in Virtual Reality

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Abstract

Geospatial image browsing is a way of organizing images according to their spatial coordinates on a geographic map. Due to the rise of smartphones, the required location data is becoming common and easy to access. Like any other method for browsing images, geospatial image browsing has several downsides of which some can be mitigated by the use of virtual reality. As virtual reality is a new platform ways for visualizing and navigating these images is not well researched. We created three different visualizations (park sign, floor and panorama) and two navigation methods (flying and teleportation) to research effective ways for visualizing and navigating images using maps in VR.

Using a comparative study on the different combinations of visualizations and navigations, we analyzed the results pertaining to VR sickness and user experience to determine which combination was better suited for navigating our visualizations. The results show that for the park sign and panorama map, teleportation was the most effective navigation, whereas for the floor map, both flying and teleportation were suitable.

Based on these results, a second comparative study was conducted on three combinations evaluating user experience with regards to image browsing. All three combinations were rated as useful, easy to use, easy to learn and satisfying by the participants. Furthermore, the interview data of the participants is used to show potential benefits and drawbacks of the system for future use and research.

Contents

1 Introduction

1.1 The increasing need for image browsing

Billions of images are stored online, and this number has substantially increased over the past decade. In 2014 alone, photos were uploaded and shared at a rate of over 1.8 billion a day [17]. The number of images shared daily on social media websites like Snapchat, Facebook and WhatsApp, has more than doubled every 2 years since 2008 [18].

The advances in technology, availability of smartphones with cameras and the readily available internet connections through widespread Wi-Fi, 3G and 4G mobile networks, have made sharing images online a daily activity for many people. With the increasing size of the large image repositories, the ability to access and browse through these repositories has become increasingly re difficult. This results in an increasing need for new techniques to assist people in image browsing and to help them deal with the huge amounts of image data. The large sizes of these image repositories therefore force developers and interaction designers to think about new and better ways to access, explore and browse them.

1.2 Different options for image browsing

Over the years many different tools for image browsing have emerged to deal with the problem of browsing large repositories. The different ways of approaching this problems consist of dealing with a combination of one or more of the following aspects: visualization, navigation, filtering and ordering.

Visualization deals with the different methods for displaying the images. The most common form for image browsing is the 2-dimensional (2D) grid, which places images across the screen along rows and/or columns. A common example of this is the Google Images visualization (figure 1)

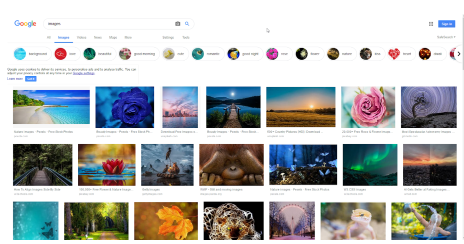

Figure 1: 2D grid layout from Google Images

Navigation on the other hand, deals with the different ways of moving through the image repositories. Therefore, navigation techniques in image browsing often refer to navigation of a visualization. The most common forms of moving in a 2D grid are panning and magnification. For example, the Google Images display (figure 1) uses vertical scrolling to vertically pan through the resulting images. These images are all small version or thumbnails or the actual image. This resizing allows for more images to be displayed simultaneously. Selecting an image magnifies it and showing more details (figure 2).

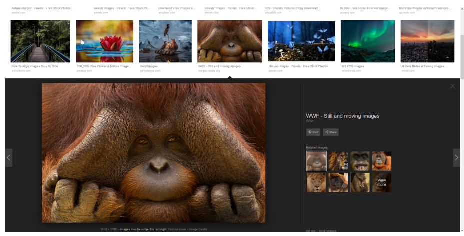

Figure 2: Scaling image sizes and magnification from Google Images

Filtering is a process used for preselecting the data before visualization. This process uses data and/or metadata from the images in the repository and selects a subset of the original repository. While the image data consists of only color values, computer vision techniques such as object recognition can be used to generate concrete keywords to filter on from the objects detectable in the image. Metadata that can be used to filter on includes, but is not limited to, date and time, location and keywords created by users or programs. Multiple filters can be applied in various combinations to get even smaller subsets and more refined data. In the top of figure 1 the user can put in a query which will be used to filter the image data on.

The ordering of images consists of sorting data according to certain criteria used in the visualization. Therefore, it is closely linked to both visualization and filtering. While a grid would pertain to the positions on which to display an image, the ordering would dictate which images are placed on each position in the grid. The aspects of ordering are similar to those of filtering, but whereas filtering creates a subset of images according to boundaries based on these aspects (such as “images between 1960 and 1961”), ordering focuses more on the gradients between the boundaries (such as “ascending order of time”).

The different examples of these aspects are general common approaches for image browsing. There are many techniques that focus on certain aspects and excel in specific contents. Most research currently is done on filtering as, especially for 2D visualizations, for most platforms there are established standards.

1.3 Geospatial image browsing using geographical maps

Automated processes which are present in most smartphones, incorporate the GPS coordinates of taken pictures into the metadata of the image [27]. In 2017, an estimated 85% of all photography was done using the smartphone [7]. Because of this, many photo browsing tools offer a map-based browsing option. An example of this is Iphoto (figure 3). Here, the photo collection is visualized by placing images on a map according to their spatial coordinates embedded in the metadata of each image. Navigating these maps usually involves dragging the map around and zooming in and out of locations. Doing this makes it easy to browse datasets where the geospatial location has relevance to the user. However, as it would be unfeasible to display large databases on a map, filtering is often required beforehand.

While there are many geospatial information systems (GIS) that use images for displaying certain geographical information, image browsing using maps has limited research. An interface created by Toyama et al. [33] combines geographical maps and image browsing and represent the images as markers on the map. Aside from the geospatial data being readily available, they also list several reasons as to why geographic location is important, and to photographic media in particular:

- Location is tied to the semantics of the image and can therefore say a lot about the image
- Location can offer universal context transcending language, culture and user-dependent taxonomies
- Technology is the only limiting factor to the accuracy and precision of the location data which makes geospatial ordering scale well.
- Browsing by location, whether via maps or by textual place names is well-understood and intuitive to users.
- Studies show that users associate their personal photos with event, location, subject, and time.

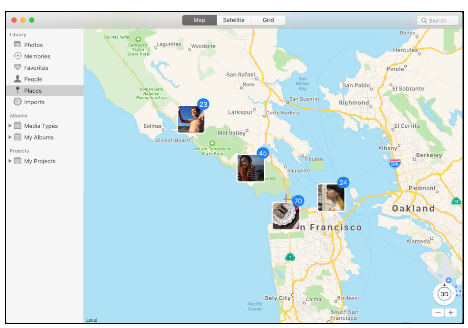

Figure 3: An example of geospatial image browsing from Iphoto

1.4 Different platforms for image browsing

Nowadays, image repositories can be accessed anywhere and also through various platforms. The dominant ways of approaching these image repositories are often platform dependent. Currently, the most common platforms for browsing images are the desktop computer, laptop, tablet and phone. The larger display of a desktop allows for more images to be displayed simultaneously on the screen compared to a tablet or phone. On the other hand, tablets and phones employ simple hand interactions such as swiping motions which are preferred by some users, due to it being feeling more natural . Zooming on phones and tablets is often done by either dragging two fingers on the screen towards or away from each other for zooming out and in respectively. However, this zooming interaction often requires using the same interaction repeatedly to achieve the desired zoom level, making the navigation slower.

In addition to these established platforms, new ways to access and deal with digital data are emerging. One of these promising ways is Virtual Reality (VR). This interaction technology encompasses the human visual field with a computer-generated virtual environment (VE). Related VR head-mounted displays (VR HMDs) as seen in figure 4, a headset equipped with stereoscopic displays, are expected to perform faster, cheaper, more lightweight and easier to use in the near future. These developments are therefore expected to make VR headsets more common in the average consumer household in the coming years.

Figure 4: image of a VR head-mounted display

Although image browsing in VR is not that common yet, the unique characteristics of this platform make it very suitable for image access. These features include the wide field-of-view (FoV), a high level of immersion, and, if implemented correctly, a natural and intuitive way of interaction. While it is already well used for viewing panorama images, we believe that VR is suited for many other image access tasks and especially for map-based image browsing.

1.5 Research Goals

Given the intuitive reasons provided in the previous section, we argue that VR, once established as an additional platform complementing desktop computers and other mobile devices, will be a very suitable, if not superior way for map-based image access and photo browsing. Yet, this will only be true if and only if the related tools are implemented properly, provide the necessary features in the right way, are intuitive and easy to access, user-friendly, and efficient in their operation. Scientific research is needed to explore various aspects in relation to this and identify optimal solutions. In this thesis, we are focusing on two major aspects related to map-based image browsing in VR.

1. What is the best representation for maps in VR when used for image browsing?

There is an infinite number of ways to represent a map on a screen. While certain standards have become established on flat 2D screens for PCs and mobile devices, immersive HMDs used in VR provide much more options. As of now, it is unclear which of those options are most suitable for image browsing.

2. What is the best way to navigate and explore maps used for image browsing in VR?

Similar to the visualization of maps on 2D screens, there are also established ways to navigate and explore these visualizations on PCs and mobile screens, using mouse or touchpad and touch gestures, respectively. While standards for VR interaction are starting to evolve and are becoming more established, it is unclear what kind of interaction design is best suited for exploring maps in an image-browsing context.

To research and contribute to the understanding of effective ways for image browsing in VR using geographical maps, we have created several interfaces consisting of combinations of visualizations and navigations. Because of the extensive time it would take to verify the user experience for each individual combination we conducted two comparative studies on the created interfaces. The questionnaire data and interviews are used to measure user experience and VR sickness, in order to evaluate the different interfaces and improve our understanding of their benefits and drawbacks.

The first study used a reduced version of the model where cubes were used as markers to represent the images. Tasks that would require the same interactions and resembled the browsing process for the second study were used to emulate the browsing experience while being able to test the navigations for each interface.

Based on VR sickness and user experience scores, for each visualization only a single navigational method was selected to be used in the second study. This second study could therefore focus directly on the user experience in the image browsing process. The user task during this second study was comprised of a search task and exploratory browsing to test approaches to using the geospatial interface.

In the section 2 we provide more context on user needs, purposes and scenarios whilst also presenting literature on maps and virtual reality. Section 3 will introduce the system that we have used for both experiments. After the implementation both studies are explained each with their own evaluation, procedure, results and discussion in the section 4 and section 5 sections. Before concluding the findings section 6 and listing future work section 7

2 Context and Related Work

The following subsections will focus on providing a better understanding of user purposes and goals for image browsing as well as scenarios where geospatial image browsing can be useful. The various benefits and disadvantages of geospatial image browsing and virtual reality will be discussed as well.

2.1 User needs and motivations for image browsing

Chew et al. [4] performed a study where they followed several people keeping meticulous diaries about their image browsing behavior. Table 1 lists the four high-level categories along with their subcategories as motivations for people to use image browsing.

Categories	Subcategories
Learning and Research	Support ongoing interests or research
	Satisfy curiosity
	Visual discovery
	Ideas
Image Access as Secondary goals	Alternative answers
	Geographical orientation
	Images as indexes
Recreating or Connecting to Remote Experience	Connecting to remote places
	Reliving past experiences
	Connecting to people and their lives
	Connect to personalities
Images as the Objects of communication	Substitute communication
	Social interaction

Table 1: User motivations for image browsing, from Chew et al. [4]

Although different user needs are addressed by different interactions and thus (often) different platforms, most of the image browsing can be categorized under one or several of aforementioned categories.

Platforms that aim towards providing a service based on one or more subcategories often have image browsing integrated in some form, even when this is not their main purpose. For example: Facebook is a social media website focusing on the subcategories of 'social interaction' and 'connecting to people and their lives' and therefore it has many interactions including image browsing to help users achieve that goal. Thus, an image browsing system has to fulfill one or more purposes to satisfy any user needs. While this categorization of purposes is not complete, these purposes can be used to establish user scenarios which in turn can be used to create the research tasks.

2.2 Leisure and exploratory browsing

Marchionini et al. [16] make a distinction between three types of search tasks: Lookup, learn and investigate. The lookup task encompasses activities that are based on having a concrete query to retrieve information, such as "question answering" or "fact retrieval". As the number of images grows, so do the results returned by the query. This makes the classification of images and algorithms to filter resulting images based on relevance a priority for directed browsing. In the case of image browsing queries, the filtering often consists of keywords pertaining to a desired image. Search engines like Google, Yahoo and Bing are designed for this type of search task with a simple interface consisting of a search bar and the results of the query. In the research of Chew et al. [4], the common use of general image search tools like Google Images was used less than 10% of all image browsing activity. Exploratory search is an information exploration activity that combines the learn and investigate tasks. With exploratory search, the user generally:

1. Has no concrete goal:

   John has no idea what to cook tonight. He uses the query "dinner recipe" to find some inspiration.

2. Has no concrete query to achieve the goal:

   John wants to find a cool background picture. The query "cool background picture" is not suited as this would be very subjective.

3. Needs a second step after an initial query:

   John needs to read up on evolutionary algorithms for his study, he searches for the top-level topic "evolutionary algorithms" and proceeds to read through abstracts to find and filter what he really needs.

Because exploratory searching lacks a simple and directed approach to an end result, focusing on query-based image filtering should not be the main approach as this does not benefit the user in his exploratory browsing. Instead, visualization and navigation become more important and the interface should be designed more towards engaging people in the search process by making a highly interactive interface, as backed by Saket et al. [29] and Marchionini [16], who argues that, "to engage people more fully in the search process and put them in continuous control", interfaces need to be designed to be highly user interactive. An often-overlooked case of exploratory browsing is leisure browsing, as argued by Wilson et al. [36]. They argue that there are many cases where there is no information oriented goal. Common examples include:

1. Need-less browsing to pass the time
2. Provide entertainment to support a laborious task
3. Having fun looking at interesting images

These situations have neither a query nor an information goal and are mainly focused on pure user experience. The joy, fun and engagement of the user with the system is not just an important aspect of the experience in these scenarios, it is the goal itself. While there is no specific task that could be used to test user experience for exploratory browsing (including leisure browsing), it is important to realize that these are factors important to the system. Therefore the user experience should be tested during the tasks to reflect whether a system is useful for fulfilling this user need. While performance is often seen as a good indicator for evaluating whether people were able to find what they wanted, for exploratory search where learning, investigating and enjoyment become more central, time spent navigating might not be a suitable measurement for user experience.

2.3 Measuring user experience using the USE

Measuring user experience (UX) is difficult. Performance for instance, has objective measurements such as speed or accuracy. Not only does user experience consist of the subjective experience of users, it is also not well-defined.

Law et al. 2009 [11], tried to gain a common agreement on the nature and scope of UX. They found that researchers tend to agree on UX as a "dynamic, context-dependent and subjective, which stems from a broad range of potential benefits users may derive from a product." However, Law et al. also notes that the understanding of user experience also differs between countries and socio-cultural factors.

A follow-up study from Vermeeren et al. [35], argues that there is no overall (accepted) measure of UX suited for any specific system. Often common UX measures need to be adjusted to suit the research needs. In our case this is especially difficult. Not only because VR is relatively new, but also because the way that we approach VR is different from the more common uses, such as: Virtual Training Environment or Gaming Entertainment.

To measure UX for our system we chose to use the USE questionnaire [13] created by Lund et al. To better suit our research we made modified versions of this questionnaire to be more reflective of our system.

While the USE is officially classified as a usability questionnaire, as Lund et al. argues: "Subjective reactions to the usability of a product or application tend to be neglected in favor of performance measures, and yet it is often the case that these metrics measure the aspects of the user experience that are most closely tied to user behavior and purchase decisions. They therefore included metrics such as usefulness and satisfaction, which we believe makes it suitable for measuring the user experience in our system. As some questions can be vague and ambiguous, we have slightly altered the USE questionnaire for our evaluation. Both studies have an altered version, which can be found in the appendices as well as the original in appendices A, B and C

2.4 Useful Scenarios for map-based image browsing

As mentioned in the introduction 1, the need for image browsing techniques is increasing. Plant et al. [25] lists several reasons why this is the case. Aside from the readily available smartphones, the storage for images has rapidly increased both on the photography devices (smartphones included) as well as external storage. This results in people making more images and taking longer periods of time to store them externally.

However, generally people don't annotate their images and even if they make annotations, these can be subjective and ambiguous. Searching for images, even in personal repositories can be an exhaustive 1-dimensional (1D) search process. Whether it is search forms, semantic clustering or chronological ordering, each approach addresses different needs and comes with its own problems and issues. Another approach to deal with this issue would be to use the geospatial metadata of the images. This geospatial data can be used to spatially order the images. As the GPS coordinates reflect a spatial position on the Earth using longitude and latitude it seems only natural to use geographical maps to display these images on. Below we have listed several scenarios in which users can greatly benefit from geospatial ordering.

2.4.1 Geographical Comparison

This user scenario is a combination of the subcategories "satisfy curiosity", "visual discovery" and in a small sense "connecting to remote places" from [ref table 1]. Because the data and imagery is displayed on a geographical map and sorted by location it is very easy to use it as a geographical filter for finding images from different countries, continents, cultures etc. Because there are large differences between continents, countries, cultures, states, provinces and even towns for a large number of topics including things such as food, architecture, art and nature, the geospatial image browser can be used as a second step after an initial query for exploratory search.

> Example scenario: Tim is interested in food in different countries. By filtering the data set on food and displaying it on the map, Tim can now easily navigate to different countries and see the photos of the food that people eat in the different countries or even between regions in large countries.

2.4.2 Exploration and area navigation

Another scenario where maps are useful is exploration. This scenario has the same combination of user motivations as geographical comparison but with an emphasis on connecting to remote places and visual discovery instead. In this scenario the interest of the user is constrained to a relatively small area. A big advantage here is that the user can navigate the map at his/her own discretion. Depending on the map, navigation can be very precise as words such as "nearby" or "close to" are relative but the geographical distance on a map is not.

Example scenario: Lisa is going on a holiday to London and wants to know the surroundings around her hotel. Instead of searching for images on the street names around her hotel she can use the geospatial image browser to navigate the surroundings. As the images placed on the streets around her hotel are taken from those places she can use the images to both memorize her surroundings as well as plan sightseeing routes.

2.4.3 Spatial knowledge and memory

People often remember the places where specific events occurred because these memories have a connection with the spatial context [20]. Traditional image retrieval requires a query to retrieve data. This makes it hard to find something if you do not know the name of what you are looking for. However, if you do know the location, a map can be used as a substitute.

Example scenario: On his holiday John climbed a mountain in the south-west of France. He wants to show images of this to his friends but forgot the name of the mountain. Using the map John can navigate to the area on the map and show the images there as well as navigate to the specific area that he visited.

While it is certainly possible to use a map to find the location name and then use the name to find imagery, not only does a map-based image browser combine both features, it also allows for more precise area navigation as stated in 2.7

Another situation where maps and spatial memories are very useful is when it comes to navigating personal data. For example hundreds of holiday pictures that are often navigated by date, can be displayed on a large map instead. This gives a good overview of all the images and allows for navigation by place rather than time. Depending on the data set this can be very advantageous as time can only be navigated one-dimensionally while geographical location is two-dimensional.

Example scenario: Walter went on a holiday to a different country 14 times in 5 years. He made a lot of pictures and wants to find the coolest images to show his friends. Using the map he can easily navigate to the images to find them as he does not know the exact dates but he remembers where he was pretty well.

2.4.4 Route-planning, spatial orientation and navigation

Route-planning is a common practice most often used in traffic to find the fastest or shortest route from point A to point B. While image browsing cannot assist in improving the speed of route-planning, it can however be used to judge other criteria. If a user is interested in traveling a more aesthetically pleasing route (e.g. road trips, hiking) rather than the fastest one, the user would need other ways to compare which route is more pleasant. One such way is image browsing. Placing images on top of the map would allow the user to judge the routes aesthetic value based on the images and thus aid the user with route-planning. Furthermore, depending on the data set, the quantity of images in certain areas can also indicate importance.

> Example scenario: Dennis wants to make a trip through Yellowstone National Park. He is unsure of what areas he should and should not visit on his travel and looks at a map of the park on his map-based image browsing application. Because of the large number of beautiful images north of Yellowstone Lake he decides to enter from the east entrance, pass by the lake and exit through the south entrance continuing his trip towards Uinta-Wasatch-Cache National Forest.

If users would like to continuously navigate an area, being actively adjusting the routes or following the route, the images could help the users to spatially orient themselves when lost. The added visual information of the images can make it easier as visual cues can assist a person with finding his or her location better, especially when the GPS is not precise enough. While helpful visual cues can vary between people, there are often recognizable objects or landmarks that appear in both the image and the surrounding area of the person. This could be a potential substitute for finding corresponding street names in the area as spatial orientation. This same effect of finding corresponding objects could also assist with detecting if a person has gone the wrong way as there would be a lack of correspondence between images and reality. Humans can recognize images faster than words as we are visual creatures and a lot of our brain is constructed around this [26][14][5]. For navigation, we create cognitive maps of the area in our heads. According to Newman et al. [23] people generally use 'landmark to landmark' for both spatial orientation and navigation. Thus images of landmarks on maps could aid in spatial orientation and navigation of users.

> Example Scenario from Chew et al. [4]: Florence thought she would drop by the Japan Centre to buy things on the way home. On her web browser, she searched for "Google maps japan centre London", which led her to the Japan Centre Website. On the "location" page of the Japan Centre site, there was an embedded Google Maps widget, which she used to find out where the Piccadilly Tube station was to get her bearings right. She also checked the address of Japan Centre, and noted the photo of the front entrance of Japan Centre at the top of the page because "it [was] easier to recognize the place". As she closed the browser window, she made a mental note of the address, the photo of the entrance, and that it was on Piccadilly Street.

2.5 Limitations and problems for geospatial image browsing

As section 2.4 shows several scenarios where the use of a map for image browsing is useful, maps have several obvious limitations:

First, not all images contain meta-data pertaining to the geographical coordinates from where the picture was taken. Even though newly taken photos often have this data, older photos do not. It is possible to add these coordinates to the metadata both manually and automatically making even older photos applicable, but images do not necessarily share a meaningful relation to a geographical place.

Secondly, merely displaying a dataset on a map can help for serendipitous browsing and leisure activities where there is not necessarily a specific user goal to complete [28]. With no knowledge of a data set, the contextual placement of images on the map can aid with achieving image browsing needs. However, this can be difficult, especially in large unfiltered datasets. Therefore, without the user bringing his/her own specific dataset, using other techniques such as filtering by keyword is often necessary for geospatial image browsing.

Furthermore, readability can be a problem with geospatial image browsing. When images share the same position (or a similar position depending on the map size) they would be placed on the same location. This would make it harder to view and navigate either image independently, especially on small screens. Furthermore, increasingly large data-sets could potentially cover the map to such an extent that parts of the map itself become hidden by the markers making it more difficult to navigate. Some possible solutions to this problem include:

Larger displays
As the readability problem is especially prominent on small screens, it would make sense to use large screens to deal with it. Desktop monitors have larger screens and thus have less readability issues compared to other devices such as smartphones. Virtual reality devices have a large field of view which also increases readability.

Zooming
This alleviates the readability problem because images in close proximity of each other get an increased relative distance when the map is zoomed in.

Clustering
Images that are in proximity of each-other are grouped together and replaced by a cluster marker. Clusters can either be navigated as groups or in combination with zooming the clusters can be unclustered when the relative distance between the images contained by the marker reaches a certain level allowing the user to individually navigate these images.

There is a multitude of ways in which geographical maps can be styled and visualized. These styles have the potential to aid the browsing activity. If a user would want to look at trains, a map with visible railroads could aid the user in navigating the map. Different filtered datasets would benefit from different map styles but this would require generating the map style based on the image dataset content.

2.6 Virtual reality benefits and image browsing literature

Virtual Reality is a fast growing platform that often uses VR head-mounted displays (HMD) to allow for an immersive stereoscopic display that often uses head motion tracking sensors to enable users to look around freely in a virtual world using their natural head-movement. While head-mounted displays are certainly not the only way to create virtual worlds and environments, our research will be tested using a head-mounted display, and we therefore will not focus on other forms of VR such as Cave or Fish Tank VR.

With over thousands of applications and millions of users [31] the VR platform is growing exponentially and image browsing has propagated to VR as well through e.g. Orbulus, Flickr in VR, Google Street View VR and Google Earth VR. These image browsing applications make use of the VR headset to surround the user with the panoramic image wrapped around them. This way they can look around in all directions which has been shown to create a strong sense of immersion [22]. While virtual reality is arguably the best platform we have for panoramic imagery, it certainly is not limited to that form of image browsing and has been used for other forms of image browsing. Some examples of this: The stripbrowser by Liere et al [34] in which several filmstrips containing different images are displayed. Buttons are used to sort images by color and using head tracking the filmstrips can be scrolled horizontally. Khanwalker et al. [9] uses a curved display for image browsing in VR. Here the user can browse a hierarchical structure of images using the bottom panel containing buttons with text or images of categories for the user to browse. The 3D MARS by Nakazato et al. [21] is another example. In their system, users fly through a VR environment filled with images arranged by similarity. After the user selects an image, the example, new images are generated that are similar to the selected image using FastMap. Schaefer et al. [30] places the user inside a spherical grid consisting of images to take advantage of the immersive aspects of the VR HMDs. The images, sorted by color, are arranged among the latitude and longitude of the sphere. Navigating the sphere is done using a combination of the Wii remote and head-tracking both the rotation and the position of the HMD.

Contrary to mobile devices and other small screen hardware, VR displays allow for large high resolution display using a wide field of view providing a less cluttered and more comprehensible virtual environment [3]. The head-movement tracking allows for looking around without external interaction. This could potentially be a significant improvement for the problem of readability in 2.5 and therefore it is one of the reasons we use Virtual Reality in our research.

Other advantages for VR are:

1. Immersion has been especially important to games, particularly challenge-based and sensory immersion, because immersion has the potential to greatly increase the user experience. As the virtual reality headset fully encompasses the users visual field, which contributes about 70% of our sensory data [15], it can create a strong sense of immersion. Lugrin et al. [12] had users play a first person shooter game both with and without VR and the players

overwhelmingly preferred the VR version of the game even when their in game performance was lower due to the more difficult realistic form of aiming in VR. As stated in section 2.2 it is important to create enjoyable systems for navigating in exploratory search. Thus VR has the potential to increase the user experience with geospatial image browsing.

2. With the user being the camera moving in a virtual space, a dynamic peephole is created, enhancing the viewing experience, spatial learning and spatial orientation. Research has shown that for mobile devices, having a dynamic peephole over a static one can increase task performance and accuracy [19][6].

3. It can enhance spatial memory and spatial understanding [3][24]. Human brains are highly optimized for 3D environment reconstruction and the depth cues from the stereopsis, motion parallax, perspective and occlusion give our brain an advantage in reconstructing those environments in VR. This has shown to be effective at enhancing user performance by increasing task completion speed and decreasing the number of errors.

Although we are not specifically looking into datasets using spatial memory as indicated in section 2.4.3, it could increase the effectiveness. This might also increase the spatial orientation for users when navigating map interfaces.

As the interfaces created for this research consist of flat map tiles with small markers placed on the tiles, we do not take advantage of the full 3D VR environment. Because the user has a spatial frame of reference and the map locations are also tied to this frame of reference, tasks where spatial ability has an impact on the performance can still benefit from the use of VR.

2.7 Limitations of virtual reality

As virtual reality is still relatively new, there are still many problems that inconvenience users:

1. An attached cable that can hinder movement and thus break immersion

2. Low frame-rate, lag and inaccurate head-tracking can lead to fatigue, disorientation or nausea. Because of the visual immersion, users rely on for accurate visual feedback. A mismatch between this feedback and reality often leads to motion sickness.

3. VR Rendering requires different images for each eye to create a parallax. This makes the rendering computationally more expensive and therefore it often requires better hardware as well.

4. Head-mounted displays can be burdensome for extended use due to them being relatively heavy.

5. It currently requires a sizeable time to set up all the hardware before use.

While we acknowledge that these problems exist, as these are mostly hardware related issues, we believe that in the near future most or all of these issues will be resolved. This would make VR convenient to use, even for small activities such as a few minutes of image browsing. While it is certainly possible right now to use VR for small activities, the long set-up time would make more lightweight devices such as the smartphone a preferred platform for small tasks, making the VR headset currently more suitable for extended use.

For several scenarios of image browsing, the platform of choice could be VR using HMDs when the headset displays would consist of simple lightweight goggles that would require nothing more than selecting your application and putting them on.

Other issues are more inherent to VR itself and these issues will most likely never be resolved: HMDs are designed to be used indoors or in predefined spaces, as they often require additional head-tracking hardware (such as the Vive base stations or the Oculus Constellation). Even resolving head-tracking would not take away that the virtual environment covers the users vision, thus making it difficult to navigate an obstructed space and/or navigate outside of a predefined space. Unlike augmented reality, which is the augmentation of the physical world with computer generated (sensory) information, Virtual Reality cannot be used for continuous spatial orientation and navigation. Furthermore, motion gestures and 3D motion tracked controllers mimicking real world interaction requires unobstructed physical space as well making VR not portable unlike e.g. the smart-phone.

Last of all, there is the open issue of visualization and navigation. While the flat 2D map representation is well-known, for VR it is unclear what visualizations will provide a benefit to the users. Likewise, navigating those same spaces might be done in various ways as well. On top of that different navigations could be more suitable for different visualizations. Hence the focus of our research has been on the combination of visualization and navigation.

2.8 Common practices for navigating in virtual reality

VR introduces a new way of interacting with the virtual environment (VE) and many new techniques have been developed for navigating VEs. A systematic review of VR navigation and locomotion techniques from 2014-2017 was done by Boletsis et al. [2]. They looked at VR locomotion and navigation of VR setups utilizing HMDs and list the following techniques:

- Real-walking: the user walks freely inside a limited physical space. HMD tracks the users position and orientation.
- Walking-in-place: treadmill-like input devices, such as the Virtuix Omni, track user movement. The treadmill translation is used as movement vector in the virtual environment whilst the treadmill keeps the user from leaving his/her location.
- Controller/joystick: simple input device with buttons for movement action.

- Gesture-based: camera's track the user gestures and translate this into input to move around
- Teleportation: the user points where he/she wants to be in the virtual world. On activation, the system instantly teleports the user to the desired location. Both controllers and gestures can be used for aiming.
- Redirected walking: similar to real-walking but it translates the movement distance relative to the VR space making a small real space usable for a large virtual space.
- Arm swinging: user alternately swings arms back and forth to simulate forward motion
- Reorientation: real-walking but by modifying the rotation of the user they can make the user turn around at physical boundaries allowing continuous travel.
- Head-directed: The user uses head movements of the HMD to control movement.
- Human joystick: The user stands and leans on a sensing board to produce motions that translate to movement.
- Chair-based: The user sits on a chair, which acts as an input device, and the chair rotation and tilt are translated into VR forward/backward and turning motions.

Anthes et al. [1] introduce some additional methods with more distinction between different forms of controller input. A controller that can aim at a specific location is referred to as a wand. This wand can be used to aim at a direction for rotation and orientation just like the head direction can. On top of that, they make a distinction between continuous and discrete model. Discrete implies that the movement is instantaneous while the continuous model uses difference between the normal orientation and the current orientation as input. In the discrete model the user simply looks around using his or her head while in the continuous model looking forward is the default direction and looking left would create a rotation for as long as the user is looking to the left.

3 Implementation

As stated, our research goal is to identify which map visualizations are suitable for image browsing in VR and to specify the best navigation methods for exploring such visualizations.

In this section we will explain the different implementations as well as their motivations. For the map visualizations we base our discussion on how the maps and map information is often represented in real world spaces. For the navigation methods, we look into common ways to explore 3D VR spaces and describe which ones we have implemented and why.

The similarities between the different map interfaces will first be discussed in section 3.1. The datasets used for testing image browsing can have a high impact on the usability and performance for image browsing. The base dataset is explained in section 3.2 with each study having their own section explaining how this dataset was used for the experiment.

3.1 Basic map construction

A map can be seen as a large 2D image with geospatial information on it. This image can be visualized in many different ways in a 3D space. Due to its size, such a large 2D map is internally made up out of several smaller images, map tiles, that are adjacent to each other.
The visualizations discussed below are each created by arranging the map tiles in different ways. Each visualization has the tiles on different locations and orientations in the 3D space.
As the Earth is an oblate spheroid, creating a 2D image often results in deformations. The map tiles used here are based on the EPSG:3857 Spherical Mercator projection as this is the most commonly used projection for map applications such as Google Maps. The distortion between this projection in relation to the reality is irrelevant for this study as accurate distance measuring is not required for any of the tasks and the placement of objects according to their geospatial coordinates (longitude and latitude) takes the projections' distortion into account.

For each image in a dataset, a small marker is placed on the map according to geospatial coordinates, to indicate the existence of an image at that location. When the user gets close to a marker, the image will be revealed and the marker will be hidden. The images stay revealed even when the user moves away. This way the user can see where he/she has been on the map.
Using a laser pointer that is attached to the each controller, the user can highlight images. Pressing the trigger button whilst highlighting an image will attach a copy of the image in a larger size to the users' controller. Doing this allows the user to inspect images or compare them with other images on the map (figure 5 and figure 6). As the map visualizations do not completely encompass the user, a dark-textured skybox was used as this would not be distracting.

Figure 5: Image highlight interaction

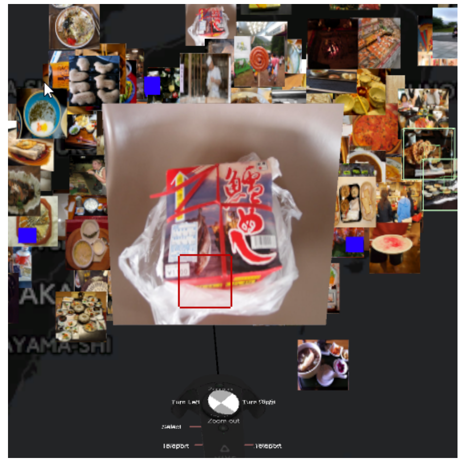

Figure 6: Image grab interaction

As explained in the introduction, navigation in 3D (as with VR) make use of a virtual camera. The usual interaction with this would be moving, rotating and zooming. However, zooming in virtual reality often results in a mismatch between the field of view (FoV) of the visual field and the FoV of the imagery and therefore we do not include zooming in the implementation. However, because the user can move around in the environment it is possible to get closer to objects and thus having them displayed in higher resolution.

Marker clustering and zoomable map tiles, a tree-pyramid structure where each tile can be subdivided in more detailed tiles, are features that can help with displaying more markers on the map, but they also introduce more varying elements to the experiment. These features will make the experiment more complex and are therefore not implemented.

3.2 Dataset for images and map visual layout

We wanted our interface to be usable independent of the dataset (assuming it can be placed in a geospatial context). While it's effectiveness might vary between datasets: the size of the dataset, spreading of the individual points or even the map used can change the effectiveness of the interface (E.g. having only images of New York would make a full world map ineffective). To make sure that our interface is applicable for all geospatial image data, we use subsets of the YFCC100M Data set [32].
The YFCC100M is one of the largest public datasets with over one hundred million images that we believe would show that our interface works for a large variety of datasets. According to the authors these images were only excluded when images would be marked either "screenshot" or "other". They purposely

selected a large portion of imagery containing GPS coordinates (both automatic [27] and manual) for spatio-temporal testing.
Because this dataset is both large, random, broad and well documented, we believe this is good for our testing purposes and will show that the interface works not for very specific datasets. However, as the geospatial images totals around half a million (48,366,323) it would be currently impossible to show all images at the same time. Furthermore because this dataset is unfiltered it would also be much more difficult to find specific types of images (e.g. Nature in Europe) due to the overwhelming number of non-nature images. Because of this we created subsets of the YFCC100M Data set to use for our experiments and the process of this is explained in for each study independently.

3.3 Visualizations

In the following section we discuss different visualization options that might be suited for map representations in VR. To structure the multitude of options, we look for inspirations in real world scenarios, such as the display of maps as billboards in parks or at subway stations, and common visualizations for large scale images in VR.

3.3.1 Park map sign

A common occurrence for maps in daily life are physical map signs. Examples of these are park maps (figure 7) and subway maps. These maps are displayed on a flat surface, a sign or billboard, and often supported by one or multiple posts. This form of display is similar to how 2D maps are displayed on screens, but in VR they are seen in a 3D perspective rather than an orthographic projection. In our VR implementation, this visualization is created by having a wall of vertically aligned tiles and the virtual camera being placed in a way that the user is standing right in front of to it.

Because this type of map is a common occurrence, similar to 2D interfaces on most devices as well as traditional physical maps, this interface is familiar to most people. This familiarity makes the interface easy to learn and navigate. Because the interface is presented in a wall like manner, from the right distance it can be viewed in its entirety. This allows the user to get a good overview of the map.

The biggest drawback of this visualization is that due to the 3D projection the angle at which a point on the map can be viewed becomes increasingly small the further the point is from the user as shown in figure 8. These acute viewing angles make tiles to the sides of the user less readable the further they are away, especially when the camera is close to the map. In addition, the flat surface offers a map only in one direction meaning the rest of the user surroundings is empty. The map also is not continuous. While Alaska and Japan are very close in reality, on our implementation it would require the user to navigate from one side of the map to the other.

Figure 7: Example of a park map

3.3.2 Floor map

The floor map is very similar to the “park map sign” style visualization. Here however, rather than being projected as a sign in front of the user, the map is shown as a plane on the ground, that can be explored by walking on top of the map and looking down for orientation. For better readability and avoiding potential neck problems from constantly looking down, markers are placed above the locations on the map. Because the user takes up space on the map itself rather than looking at it and VR does not show the legs and thus the specific position of the user, the map size has been increased. Without this, it would be difficult for the user to estimate its current location as it could overlap several areas. On the park sign map the user can easily see where he/she is aiming, as the laser pointer attached to the controller will hit a location on the map. Flying pins on the floor map are floating (as mentioned above) and aiming in 3D becomes hard when you do not have good visible feedback. Thus, the sizes of images and pins have been adjusted accordingly.
An advantage of the floor map is that the acute angles are less prevalent

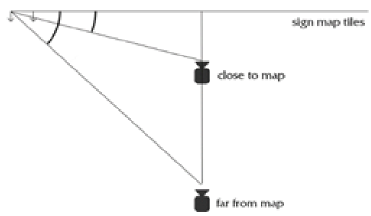

Figure 8: Problem of acute angles with the park sign map visualization

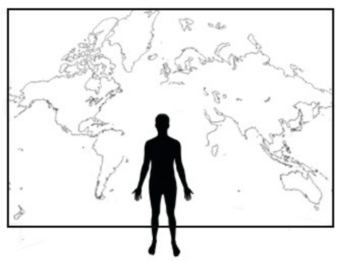

Figure 9: Park sign map front view

compared to the park sign map. The reason for this is that humans are more inclined to horizontal head rotation over vertical rotation as Bolwerk [8] pointed out. Furthermore, the placement of the markers above the locations makes it so that more of the virtual space contains useful information for the user to interact with. Rather than navigating the images looking at the map, users navigate to a location on the map after which they can look around at the markers. This has the potential to instill more presence and in turn can make the interaction more engaging and satisfying.

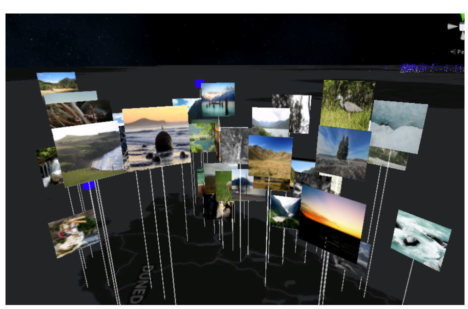

Figure 10: Floor map image view from the system

One of the common disadvantages of floor maps are potential neck problems from looking down to see the map. This is reduced by the markers floating above the map but may still be prevalent. In addition, even though the acute angles are less noticeable, it could still negatively affect readability.

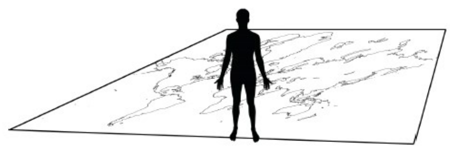

Figure 11: Floor map representation

3.3.3 Panorama map

In photography the term 'panning' refers to the camera rotating around the up-axis. A panoramic image is created when the panning of a camera is used to create wide images. Using a camera and rotating a full circle can create a 360-degree image that shows the entire surroundings of the camera as seen in figure 12.

Figure 12: 360 degrees panorama image

These panoramic images are commonly used in VR. With the virtual camera at the center, the image can be wrapped around the camera creating a cylindrical continuous image (figure 13).

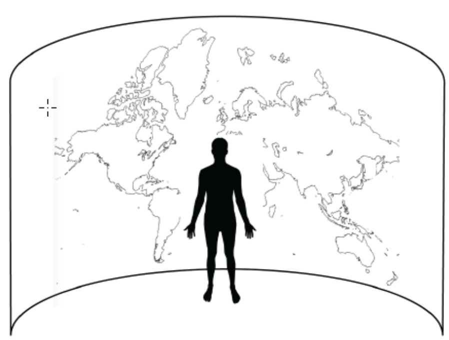

Figure 13: Panorama map front view

The most commonly used map projections (Equirectangular, Mercator) are horizontally continuous and can also be wrapped around a camera in a cylindrical shape. This map visualization that resembles a panorama surrounds the user except for the top and bottom of the cylinder being open.

This interface brings several benefits. It eliminates the problems with the viewing angles of the previous two interfaces when looking around horizontally. Because the map is surrounding the user, the user is more immersed compared to the other interfaces. It better utilizes the 3D space as the map surrounds the user. This also means that by utilizing the camera rotation the user can navigate large distances quickly.

One of the large downsides of this interface is the lack of overview of the complete map. It is also a visualization that most people will be unfamiliar with. Therefore, this interface might require more time to learn than the previous interfaces. Another disadvantage is the acute viewing angles in the vertical direction because the interface is not spherical. Yet, as horizontal rotation is more important for navigating a panorama map, this problem with the vertical viewing angles should be less severe. Last of all, adding other functionalities such as zooming are not straightforward for a curved surface.

3.4 Navigation and exploration

Visualizations need ways to be navigated and explored. Functionality such as moving to certain places on the map is therefore a critical element of the interface. We selected two methods from a wide variety of well-established VR navigations section 2.8. This selection process was based on the following criteria:

- Usable when sitting down and thus not requiring a large physical space
- Does not require additional hardware other than the components included in the VR system itself.
- Methods must remain similar in terms of functionality across our different interfaces. This makes it easier for the user to learn the navigation methods while reducing variance.
- Interaction should be easy to replicate by other VR systems that have tracked controllers.
- Does not require gesture-based interaction. These interactions are often slow and not suitable for a continuous engaging interaction.

As most prominent VR systems such as, the Sony PlayStation VR, Oculus Rift, HTC Vive, and Samsung VR, feature some sort of motion-tracked controllers. An analysis of common implementations for navigation in VR applications under consideration of the aspects mentioned above identified the following two options as most promising for our scenario: controller-based and teleportation navigation. As the teleportation movement also uses the controller for its functionality, to avoid confusion we will refer to the controller-based navigation as flying. Since it allows the user to navigate like a drone in the air the term is reflective of its implementation.

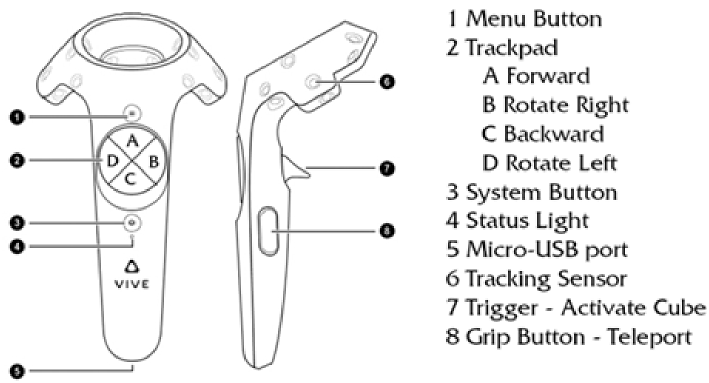

Figure 14: HTC Vive controller layout

3.4.1 Flying

For controller based interaction in our system there are 2 common solutions for choosing the movement direction of the camera:

1. Head-directed, in which the camera moves based on the direction the user is looking.

2. Wand-directed, in which the user uses the orientation of a tracked controller to determine the direction of movement.

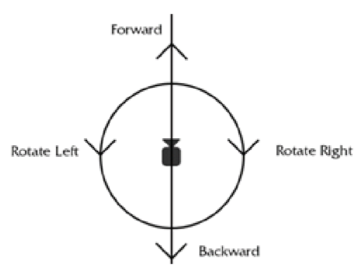

Figure 15: Controller interaction for flying navigation

Head-directed Flying
The direction that the head position of the user is facing, is the forward direction. The following controller layout is described according to figure 14. Pressing

the trackpad in the “A” location will move the user forward in that direction. Pressing the “C” location on the trackpad will move the user backward from the direction the user is looking. This includes the downward angle so that when looking straight down the A location will move the user down and the C location will move the user up.

Left and Right will rotate the user around the Y-axis (up). This is irrespective of the user’s viewing angle. The reason for this is to prevent the user from rotating into unnatural head rotations. For example, if the user is looking straight down, rotating 180 degrees would make the user look up while looking down instead which is not only confusing but rotating the head up afterwards would make the camera vision upside down.

Physics simulation is used when flying. The camera that represents the user’s head gets forward momentum to simulate the movement. The maximum speed is set by introducing drag (air resistance) which reduces the current speed by a percentage over time. When the increase of the speed by the added momentum and the drag resistance reach the same value, the maximum speed is reached.

Using momentum and drag allows the user to increase the speed over a small-time frame rather than instantaneously. A second controller can press forward to double the added momentum each step, giving the player more control over the speed at which he/she moves. Using momentum for the flying navigation allows users to have more control over their speed especially when it comes to small movements on a large map.

Expected advantages:

1. More flexible as it allows for more control regarding the position of the user than teleportation.

Expected disadvantages:

1. More complex / harder to control since it requires more input to achieve the same position as the teleportation method and more spatial awareness for orientation.

2. Because the user continually uses his/her head to steer this navigation can cause more nausea.

3. For navigation on the flat map, to fly sideways requires the user to look away from the map (90 degree angle).

Wand-directed flying
Wand-directed flying works similar to the head-directed flying, but rather than using the users head rotation for determining the move direction, it uses the controller direction instead. However, when pressing left and right on the

trackpad the rotation around the Y-axis remains intact. When pressing forward the camera will gain momentum in the direction of the controller where forward is being pressed on the trackpad. In the case of two controllers the vector directions are added together. So, if the user is facing forward, to move up he aims his controller upwards and pressed forward or downwards and presses backwards.

Expected advantages:

1. Allows for the most control compared to both teleportation and flying with head direction.
2. Allows the user to look in a different direction than he/she is moving (this is especially beneficial when moving up and down as it's less stressful on the neck compared to flying with head direction).

Expected disadvantages:

1. Unintuitive and thus more difficult to learn especially when using 2 controllers simultaneously.

3.4.2 Teleportation

Teleportation often refers to the fast or instantaneous transportation of energy or matter from one place to another. To use this as a functional navigation the user must be able to accurately control the destination of the teleportation.

By holding down the grip button (button 8 according to figure 14) on the controller a parabolic pointer is shown from the controller. Where the pointer intersects with the map a circle indicator is shown around the intersection to increase the visibility of the end location. Using the pointer to aim, the user can select a location and when he/she releases the grip button the camera, and thus the user, transports to the location.

Similarly to the acute angle problem explained in the section 3.3, small changes in the angle of the controller using a straight line will result in very large differences when aiming in the distance. A parabolic pointer reduces this problem.

While most transportation is instantaneous, our implementation translates the user over the span of a few seconds. Through personal testing we found that instantaneous teleportation was both disorienting and could cause headaches, while a fast transition did not. Moving slower to the new position should also help in maintaining a better awareness of one's position in relation to the map and the surrounding area on it.

After teleporting, the user can get closer to the map or further away using the A and C region on the trackpad respectively. The rotation is the same as for the flying navigation.

Expected advantages:

1. Simpler, thus easier to control.
2. Less time spent navigating thus less discomfort and nausea.
3. Requires few interactions for large navigation distances.

Expected disadvantages:

1. Not very flexible as there are limited motions and target locations.
2. After switching location, the user always gets close to the map.
3. Second controller offers no additional functionality.

3.5 Materials, experiment setup and software

The experiment was done using the HTC Vive (77H02568-09M Revision A) which has a display size of 1080 x 1200 per eye, a 90Hz refresh rate and a field of view (FoV) of 110 degrees. Both Vive Controllers are used during the experiment.
The computer used in the experiment is equipped with the EVGA Geforce GTX 1080 Ti FTW3 video card and an Intel i7 3770 processor. The high end video card is used to maintain a high frame-rate as low frame-rates can be a contributor to VR sickness and VR rendering is computationally taxing on the video card as mentioned in section 2.7. During both studies, the participants are seated on a non-rotary chair as standing for long experiments could cause leg pain and fatigue.

The system was created using Unity personal edition 2018.2.16f1 (64-bit) and C# as the scripting language. The SteamVR API (renamed to SteamXR for newer versions) made it possible to interact with the HTC Vive and making it relatively easy to switch between other VR HMDs as well. To allow the researcher to monitor the participants and control the datasets, the system was run in the unity player rather than exporting a standalone executable, which would reduce performance costs.

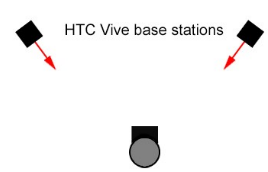

Figure 16: Room setup top view

4 First study: Researching the effectiveness of navigation for each visualization

4.1 Purpose

The first study was used to evaluate the effectiveness of both navigational methods (flying and teleportation) for each individual visualization. The results of this were used to eliminate one of the two navigational methods for each visualization. As navigations can be better suited for different visualizations, a comparative test is done for each individual visualization rather than across visualizations. For example, the teleportation might be better suited for the park sign visualization, whereas flying might be better suited for the panorama visualization.

The first study did not use images for its evaluation, but instead it used simple tasks that are reflective of the interactions required in the final system. Doing this allowed for a better focus on the navigational aspects of the interactions and have the data remain relevant to the final system used in the second study.

To evaluate the different interfaces, the focus for the first study was primarily on the usability and user comfort, such that is does not cause nausea or motion sickness for the user. Because user satisfaction was going to be the primary focus of the second study, this was also evaluated during the first study.

The first study thus served to:

- Reduce or avoid problems with VR sickness in the second study
- Reduce the number of independent variables for the second study
- Provide feedback and a better understanding for the implementations including possible benefits and drawbacks

By answering the following research questions based on the evaluated data:

1. For each visualization, what is the most effective (in terms of UX and VR Sickness) navigational method?
2. What are the relations between the user experience and the user discomfort with regards to the navigations and visualizations?

4.2 User task and implementation changes

Because the user is not browsing images in the first study, the markers on the map will not transform into images when the user gets close. This also disables the ability for users to grab images with the controller. Instead the markers can change in size and color and can display a number on the sides of the marker. This was used to make the tasks reflective of the second study.

The second study tasks are composed of four steps:

1. The user is explained a scenario related to a certain location
2. Using the navigation interaction of the map, the user moves towards the location
3. When the user gets close to the marker on the location, the markers transform into images
4. The user find and/or evaluates the images in the area around the target location

The first study task is also comprised of four steps that emulate the above four steps:

1. A marker on the map turns red and is enlarged indicating a certain location to the user
2. Using the navigation interaction of the map, the user moves towards the location of the red marker
3. When the user gets close to the red marker on the location, the surrounding blue markers turn cyan. Numbers are shown on the red marker as well as on the white markers surrounding the location of the red marker (figure 17).
4. The users goal is to find the teal marker that has the same number as the red marker and select it using the controller

Each step from the first study emulates the corresponding step from the second study task. Rather than a named location, the location is visible by a red marker and instead of looking at the images, the user looks at numbers. The red marker is chosen pseudo-randomly so that it changes between short and long distances, requiring users to travel variable distances between tasks. The area is based on the tile distances where the reveal area from step 3 is an area of nine (3x3) tiles of the map, the short distance is between three and five tiles away from the red marker whilst the long distance is the remaining markers more than five tiles away.

The number of targets is defined by a time constraint so that each testing phase will have a set amount of time. After this time limit has been reached, no new markers will turn red and the play can finish his/her last task.

Figure 17: Step 4 of the first study task

4.2.1 Dataset

To avoid problems such as readability and the variance that clusters of markers would have on the task orders, we have created a set of markers that is the same for all tests in the first study.

The data set was created using the following steps:

1. Remove all markers from the South Pole, North Pole and markers on the sea and islands that are almost invisible on the map (comprised of only several pixels).
2. For each of the remaining markers of the 500M markers of the YFCC100M set:
   (a) For each tile of the map that contains at least one marker:
      i. Randomly select one marker
      ii. Delete all markers on that tile with a distance closer than X to the randomly selected one
      iii. Repeat steps i and ii until the distance between any two markers on that tile is larger than X
      With X being approximately 200 km

The North and South Pole contain very few images, resulting in the tasks working differently. It is also possible to be overlooked easily by the user due to them being largely insignificant in most map applications, which is why we removed them from the dataset.

The resulting dataset projected as markers on the map is displayed below (figure 18

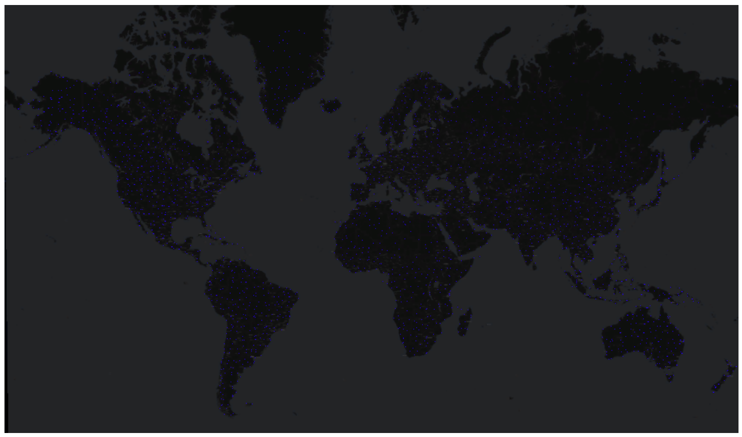

Figure 18: Image of the first study dataset

4.3 Evaluation

As stated earlier, the primary focus of the first study is to evaluate the usability and VR sickness of each combination of visualization and navigation with the user experience being secondary. To measure the VR sickness among participants we chose to use the VRSQ questionnaire [10] as it seems suitable for our system and was designed specifically for measuring VR sickness. The USE questionnaire selected for the second study is an extended usability questionnaire measuring user satisfaction and usefulness aside from usability. Some questions in the questionnaire are too vague and therefore some questions have been adjusted to better suit the study (see appendix B).

4.4 Procedure

Because the majority of the participants had Dutch as their native language, the experiment was conducted in Dutch and English phrasing was translated in Dutch. The conducted questionnaires remained in English and could be translated by the researcher if requested by the participant.

At the start of the experiment the user is explained the high level goal of the study: *"In this experiment, you have to successfully perform some simple navigation and selection tasks. Yet, we are not that interested in your actual performance, but more in how easy and comfortable it is to do this tasks, how much you like the experience, and if there are any negative side effects like* *nausea or motion sickness."*

After the introduction, the user had to fill in a consent form (appendix D) which informed them of the risks and possible side-effects of the VR experiment as well as allowing for the usage of the gathered data. After the consent form was filled in the user was presented with a demographic form to establish information about their age, sex, handedness and experience with both map interfaces and VR devices. This data was gathered as it could potentially influence the results.

After these two forms the participants were explained the task using a step-by-step picture explanation of how to complete a single task. The researcher would help with putting on the VR headset and making sure it was calibrated properly before beginning with testing.

The visualization order was counterbalanced to avoid bias and for every visualization:

1. The user would practice using the first navigation for two minutes and understanding the controller interaction.

2. The user would practice completing the task using the first navigation for a single minute

3. The user would complete tasks for four minutes

These three steps would be repeated by the user by the user for the second navigation. After completing both tasks for the given visualization, the participant would then fill in both the USE and VRSQ questionnaires and be asked for some short comments on their experience with the two navigations before moving on to the next visualization. Subsequently, after completing this process for all three visualizations a short interview was conducted to get a better understanding of experience was performed to conclude the experiment.

4.5 Participants

The first experiment was tested on a total of 26 participants. 3 of these users did not complete all 6 tests due to nausea or other physical discomfort. All participants were between the ages of 18 and 34. This age range was selected as this is the most common age among VR device owners and thus most reflective of the actual user base.

Below are graphs about the demographic information of the participants (

4.6 Results

4.6.1 VRSQ and sickness

No single element on the VRSQ questionnaire had an average above 1, meaning that for the average user there was none to slight signs of VR sickness.

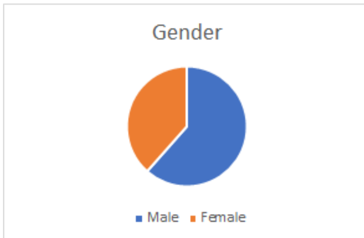

Figure 19: Gender breakdown for the first study

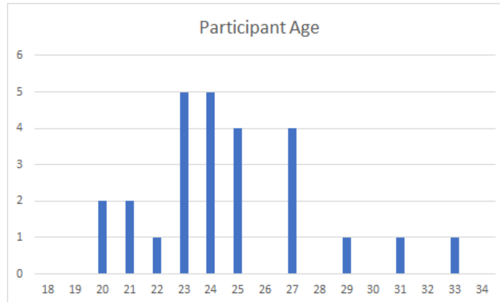

Figure 20: Age breakdown for the first study

Figure 21: VR experience breakdown for the first study

Using paired t-Test the navigations were analyzed with a confidence interval of 95% and showed that for the park sign map the teleportation navigation was significantly better than the flying navigation $t(22) = 2.09$, $p = 0.049$. For the other two visualizations, no statistical significance was found between flying and teleportation with regards to VR sickness.

The VRSQ data can be found in appendix G

Interview data and observation

The opinions on the flying speed were divided. While some users indicated that they preferred a faster speed, other users found it was going too fast and could cause nausea.

However, most people that did have problems with nausea, indicated that this was primarily caused by rotation using the controls. This was especially present when looking down on the floor map while rotating. Because the chair does not rotate, the user is limited in body rotation. When the user would teleport past the target on the floor map, significant rotation from the user was required to correct this. While it was possible to teleport backwards using the controller to aim at locations not visible by the field of view, only two users came up with this solution. Looking at the results and averages, this rotation sickness could explain why the Floor map has the highest average sickness as well as the highest variance.

4.6.2 USE results

Answers to the USE questionnaire were rated on a 7-point Likert scale. From "strongly agree" to "strongly "disagree". For each category of the USE questionnaire ('usefulness', 'ease of use', 'ease of learning' and 'satisfaction') the average score was calculated for each participant. Afterwards a paired t-Test was used to analyze the categories between the navigations for each visualization separately using a confidence interval of 95

Park sign
The results of the paired sample T-test were significant for the following:
Usefulness: flying (M=5.27, SD=1.31) and teleportation (M=6.14, SD=0.69) conditions; t(22) = 3.71, p = 0.001.
Ease of use: flying (M=5.24, SD=1.63) and teleportation (M=5.86, SD=0.69) conditions; t(22) = 2.52, p = 0.019.
Satisfaction: flying (M=5.33, SD=1.81) and teleportation (M=6.12, SD=1.07) conditions; t(22) = 3.01, p = 0.006.

Showing that teleportation is better than flying for the sign map

Panorama

The results of the paired sample T-test were significant for the following:
Usefulness: flying (M=4.84, SD=1.75) and teleportation (M=5.86, SD=0.51) conditions; t(22) = 3.85, p = 0.001.
Ease of use: flying (M=5.07, SD=1.10) and teleportation (M=5.75, SD=0.63) conditions; t(22) = 3.22, p = 0.004.
Satisfaction: flying (M=4.90, SD=2.65) and teleportation (M=5.89, SD=0.76) conditions; t(22) = 3.04, p = 0.006.

Showing that teleportation is better than flying for the panorama map

Floor
The results of the paired sample T-test were not significant for any of the four categories with regards to the floor map

The USE data can be found in appendix H

Interview Data
The data gathered from the interviews is based on the 23 people that completed all tasks. Table 2 shows the user preferences. The preferred combination is displayed as the first choice, and for each individual combination it shows which of the two navigations the user preferred.

	First choice	Preferred	Undecided
Panorama TP	3	13	3
Panorama Fly	4	7	
Park Sign TP	5	17	2
Park Sign Fly	1	4	
Floor TP	3	7	3
Floor Fly	7	13	

Table 2: User preferences for the different combinations

Users generally disliked the rotation necessary for teleportation on the floor map the most. The park sign map did not require rotation, the panorama map only required rotation for finding the target whereas the floor map also needed rotation after the user got into the proximity of the red marker.

Teleportation was usually preferred by users because it was faster while flying was more associated with fun and the immersion of travelling (traversing) the map. Flying was often seen as less fun because it was significantly slower and required more interaction to reach a target. While flying allowed for easier compensation of mistakes as well as small movements, this was almost never needed on the park sign and panorama map and thus teleportation was generally seen as the better choice.

As for the map visualizations themselves, the park sign map offered a clear overview and thus made it easier for users to find the red marker. The panorama map lacked this type of overview but it was fun to navigate as it is surrounding the user and thus more immersive. The floor map offered a lot of users both overview and immersion. Several users remarked specifically with the floor map that the map had a direction and all text on the map and markers were facing that direction. This made some people navigate the map by having their default front view always rotated towards the North Pole.

4.7 Discussion

After analyzing the data from the first experiment, it was noticed that the USE questionnaire was missing one question that could have affected the results. The question "I quickly became skillful with it" was missing from the created questionnaire and the ease of learning category was thus affected. Based on the interview data and the observations of the participants interacting with the system, we believe this question would have slightly favored teleportation. However, it would not have made a significant difference when it comes to the final conclusions of the system as detailed below. Based on the results from the questionnaire as well as the interview data we conclude that:

For the park sign map
Teleportation is more effective on this map than flying with a significant advantage on VR sickness as well as 'usefulness', 'ease of use' and 'user satisfaction'. These conclusions supported our earlier hypothesis of teleportation being better for the park sign map than flying.

For the panorama map
Teleportation is better than flying on the panorama map with a significant advantage on the categories of 'usefulness', 'ease of use' and 'user satisfaction'.

For the floor map
The floor map showed no significant difference between the two navigational methods from the measured data for both the VRSQ as well as the USE questionnaire.

From the interviews of the users there are different aspects to each navigation that are liked by users. So while flying is not significantly preferred over teleportation, the reasoning given why we thought flying would be better fitted was supported by the data collected from the interviews.

The biggest problem people had with teleportation was due to how the user often has to rotate whilst being close to the red marker. While flying therefore seems to be better for when the user is unable to fully rotate his/her body, it is entirely likely that if the user is standing or using a rotary chair that teleportation is preferred over flying. However, as the scenario for our study is aimed at a seated position we will be using flying for the floor map rather than teleport.

For teleportation
Teleportation was viewed as the faster way to interact and move. Our hypothesis expected the panoramic map to be the best suited for it as it was easier to aim at every point of the map without changing the distance to the map. However the results show no significance between the park sign Map and the panorama map when using teleportation (alpha = 0.05) thus rejecting our hypothesis that the panorama map would be the best option for the teleportation navigation.

Regarding VR Sickness
Our hypothesis that teleportation gives less motion sickness and discomfort was partially correct. The navigation on its own creates less motion sickness as evidenced by the interviews but it is the necessity to rotate more that creates the motion sickness. This is why the park sign map teleportation does significantly better than flying where no rotation is needed, followed by the panorama which needs rotation only for travelling to the marker but not for finding the matching marker. Teleportation loses on the floor map where rotation was often necessary when at the correct location as a full body rotation is not possible in a seated position.

Our hypothesis also indicated the panorama visualization to have the highest VR sickness due to the lack of overview which could cause disorientation. However the floor map due to its increased need for rotation seemed to have the highest VR sickness and thus our earlier hypothesis regarding this was rejected.

5 Second study: A comparison for image browsing with regards to user experience

5.1 Purpose

In the first study we evaluated the different navigational methods for each visualization. This interface excluded image browsing and used tasks that required navigational actions to be completed. In the second study we evaluate the effectiveness of the remaining visualization and navigation combinations with respect to the users image browsing experience. Based on the data from the first study, for each visualization only one navigational method was selected. The selected combinations are as followed:

1. Park map sign and teleportation
2. Panorama map and teleportation
3. Floor map and flying

The second study uses the final system, which introduces image browsing to the interface and adds interactions with images changing how the user interacts and experiences the interface. However, the methods for navigating the VR space remain the same. During the first study moving around in the VR space was the biggest contributor to VR sickness. As there are no changes in the method of moving between the first and second study, it is unnecessary to reevaluate this.

Thus, the second study attempts to give answers to the following research questions:

1. What visualization-navigation combination is most effective (in terms of user experience) for browsing images on geospatial maps in VR?
2. What is the relation between the different aspects (satisfaction, usability, performance) and the user experience and what is the relation between the different interfaces.

5.2 Evaluation

As mentioned in the first study (section 4), the tasks for the second study consisted of four distinct steps:

1. The user is explained a scenario related to a certain location.
2. Using the navigation interaction of the map, the user moves towards the location.
3. When the user gets close to the marker on the location, the markers transform into images.

4. The user find and/or evaluates the images in the area around the target location.

Most of the tasks used to measure image browsing interfaces and systems are centered around the user finding specific images (target search) or representing images according to some criteria (journalistic task). However, the interface was designed to accommodate exploratory browsing, which does not have a clearly defined end-state. There is no accuracy, correct target or set point of completion other than a time limit that can be used to quantitatively evaluate the user experience for exploratory browsing. Still, the users would need some directions and incentive to explore the map. As there are different goals with which users could approach the interface, the scenarios should reflect those different approaches. To measure the user experience we will be using a modified version of the USE questionnaire listed in appendix C. We also measured the time users took for each task to see if there was no significant difference between datasets and as the landmark scenario has a target search element to it, if this is viable in VR.

5.3 Scenarios and user task

The scenarios used here are based on the geospatial scenarios listed in 2.4. Here we identified several cases in which map-based visualizations can be useful for image browsing. Because we are using VR and our dataset (which will be discussed in the next section) does not contain personal images of the participants, the following cases are applicable for our experiment:

1. Geospatial comparison (comparing over large distances or areas 2.4.1)
2. Area navigation and exploration (close area navigation 2.4.2)
3. Geospatial knowledge (using geospatial information to navigate and attempt to locate certain imagery 2.4.3)

Because the visualizations use a world map, the difference between the first and second scenario will be solely based on the need for comparison. As the majority of the participants' first language will be Dutch, the scenarios are translated into Dutch for them. The first two scenarios are focused on going to one or more locations and looking at the images of the locations. The third scenario is based on finding a target (e.g. a landmark such as the Eiffel tower) and then using the geospatial knowledge a user has to locate the specific landmark on the map. This scenario is more of a task-like interaction with the map than the other two as it has a more clear end-goal. It is such a significantly different way in approaching the map that it should be included as part of the test.

For this third scenario the participant was asked whether he/she had visited any countries outside of the Netherlands. If this was the case, the participant would be asked if he/she could find a landmark using the map interface and what landmark that would be. If the participant either had not been outside of the Netherlands or was unable to recollect any notable landmarks he/she visited, the participant was asked to search for a landmark that the participant would like to visit and of which he/she had a reasonable idea of the location of said landmark. If this also was not possible for the user the scenario would be skipped completely.

There are multiple tasks for the user to test on each combination that cover the same steps mentioned above but use different scenarios, locations and datasets. Each participant would get a specific scenario only once to avoid prior knowledge of the images at the locations. The number of tasks is defined by a time constraint. Each testing phase had a set amount of time. After this time limit had been reached, no new scenario would be given but the participant was allowed to continue the current scenario until it reached the scenarios individual time limit. This scenario time limit is set to guarantee that participants will have at least spent eight minutes or six scenarios for each interface whilst also making sure that there is a fixed maximum time for each participant. The different scenario sets used for the evaluation are listed in the appendix F.

5.3.1 Dataset

Using topics such as nature, architecture, museum, food and flower as filter keywords results in subsets with clear and distinct topics whilst being general enough to create tests that would show that the implementation works independent of the dataset. Filtering on tags including countries and other local places such as New York could also be used in our application. However, as we used a map of the earth for testing purposes rather than a local map, filtering on local places would have resulted in a visual overload of markers. Too much would be displayed on a certain location, making parts of the map unreadable.

For the scenarios created we filtered the datasets on the keywords and also split these results among countries. The final subsets were created by randomly adding markers to the set that would not intersect with other markers already present. After the subset reached the limit of markers allowed, which is around 2000 for performance purposes, the subset was completed. These subsets were then saved and used for all participants so that different subsets could not be the cause of deviance.

5.4 Procedure

The procedure of the second study was structured similar to that of the first study. It starts with an introduction and high level explanation of the study goal using a Dutch translation of the following:

"This experiment is used to evaluate user experience, when browsing images and photos on maps, in virtual reality. We are interested in your feedback regarding several aspects such as whether it is easy to use and gives an enjoyable

experience. To do this you have explore the map according to a few different scenarios on three different map visualizations after which you fill in a short questionnaire. After doing this for all three maps, we will interview you on your opinions and experiences with the different interfaces which will consist of a few open questions."

The users were also given an explanation that if they were feeling unwell, unwilling or unable to continue for any reason they could take a break or stop the experiment at any time. Subsequently, the users were then submitted to the same consent form and information about possible side-effects of the first study (appendix D), followed by a demographic questionnaire for those that did not participate in the first study. After filling in these two forms the participants were explained the general workings of the system, button functionality, how images appear and a brief explanation of the three visualizations. Following this the user was explained the basic structure of the scenarios and that the experience measured using the questionnaires at the end of each interface is the focus of the study, not the speed at which they browse the images. Each scenario had a time-limit that the researcher would notify the user of, but the user could also notify the researcher when he/she was done with a current scenario so the next scenario could be started.

After the explanation, the participant was helped by the researcher to put on the VR headset and the system was calibrated concluding the set-up for the experiment. At the start of every new visualization, the user would be given time to practice navigating around the map until they were confident in their understanding of the navigation. To finalize the practice, the researcher would show images of the 'museum' dataset limited to Spain and instruct the user to navigate to the area, inspect, grab and release the images with the controller. This was done to make sure that each participant understood the full range of possible interactions with the system before fully starting the experiment.

Once the practice was completed, the user would be submitted to three or six scenarios (depending on the time spend on the first three scenarios), before filling in the USE questionnaire and giving a small interview about their experience. This process was repeated for all three interfaces, the order of testing of the interfaces as well as the scenarios used were counterbalanced. Finally, on the last page of the questionnaire the participants would give each interface a grade between 1 (lowest) and 10 (best) before being submitted to a more extensive interview consisting of several open questions.

5.5 Participants

The second study concluded with a total of 35 participants using the same demographic selection as with the first study. From the 35 participants, 16 had already participated in the first study whereas the remaining 19 were completely new to the study. Only one participant failed to finish all three visualizations and for the purposes of analyzing these results were excluded from the data.

The same demographic survey was used to gather data as during the first study. While new participants would fill in this survey, for the participants that performed in the first experiment the demographic data was already collected. As users from the first study would presumably be more effective with the system due to their prior experience and more interested based on their willingness to do a second study, we made sure that at least half of the participants were unfamiliar with the system to eliminate bias. This way, it was possible to analyze if there was a significant difference in results between both new participants and those that participated in the first study. However, no significant difference was found in the results between these two groups and thus this will not be mentioned when discussing the study results. The breakdown of the participants is the diagrams below (figure 22, figure 23, figure 24).

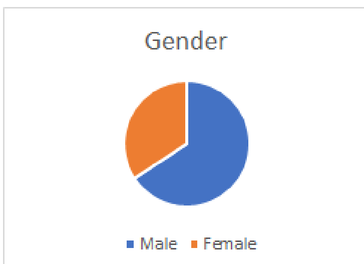

Figure 22: Gender breakdown for the second study

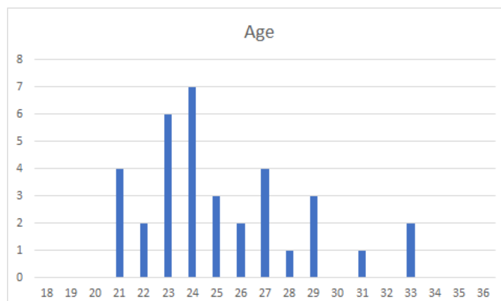

Figure 23: Age breakdown for the second study

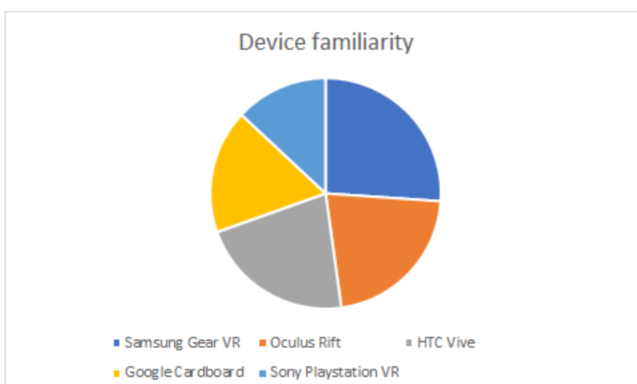

Figure 24: Device usage breakdown for the second study
Note that some users had experience with multiple devices.

5.6 Results

5.6.1 USE

Results: Below are the average scores and standard deviations of each category from the USE questionnaire with respect to the different visualizations. Statistical analysis between the three interfaces for each different category using Repeated Anova ($\alpha < 0.05$) revealed no significance difference between each of the categories.

In depth analysis of the individual categories also revealed no significance. Data from the USE can be found in the appendix F

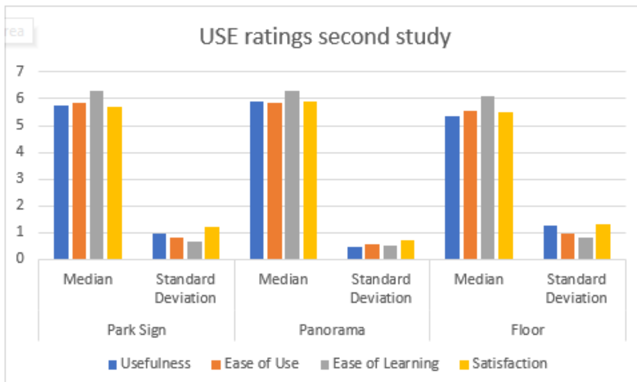

Figure 25: User Rating mean and standard deviation for each category of the USE questionnaire

5.6.2 User Scores

There is no significance in the data between the user scores. Looking at the frequencies of the scores given by the users the Floor interface has the highest standard deviation (figure 26, figure 27 and figure 28).

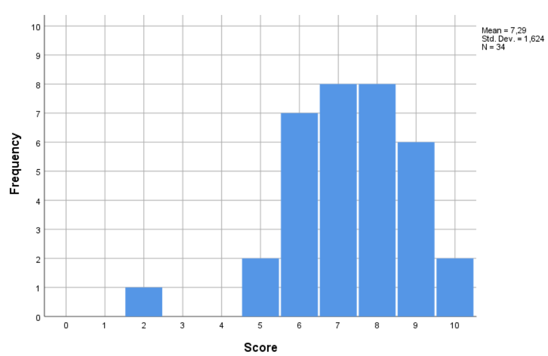

Figure 26: Scoring frequency for the park sign visualization

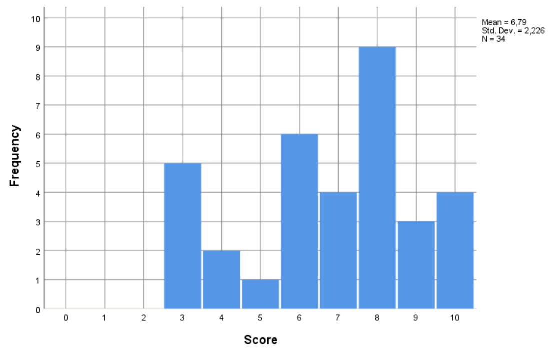

Figure 27: Scoring frequency for the floor visualization

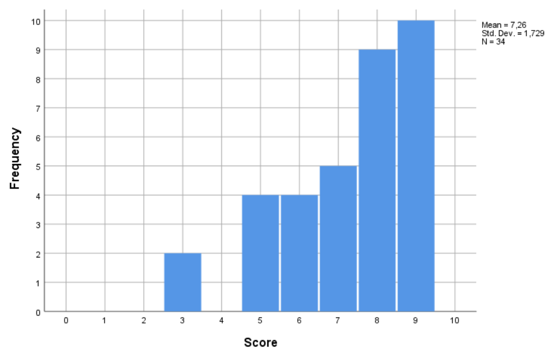

Figure 28: Scoring frequency for the panorama visualization

5.6.3 Interview Data

Image interaction

The ability to grab and hold enlarged copies of images with each individual controller as evaluated by the users showed the following:

- The overwhelming majority of users (23) were very satisfied with this interaction and when prompted what they would change they said it was doing everything it needed.
- Some users (7), including those present in the previous category said that the image grabbing was not necessary in the floor interface, because this interface already contains larger images and can be viewed at a closer distance than the other two interfaces as the user can “fly through them”.
- Other users (6) thought the images were either too close or had to hold the controller in a different angle to be able to see the image. When observing users using the HTC Vive there were different postures that users would be sitting in. If users would have their upper arms straight down along their torso, putting the controller forward with the use of only the elbows

and not the shoulders, users would comment that the images were to close. As the angle of how the user holds the controller mattered for the image angle being incorrect, users that would hold the controller closer to the body would automatically need to rotate the controller downwards to see the image from a straight angle compared to users holding the controller more forward figure 29.

- The remaining comments consisted of alternative ways to interact with the map such as, replacing the image grabbing by use of clicking to a hold/release interaction or resizing the images when clicked rather than grabbing them, and additional functionality for the system that were outside of the research scope such as adding the options to remove and save images.

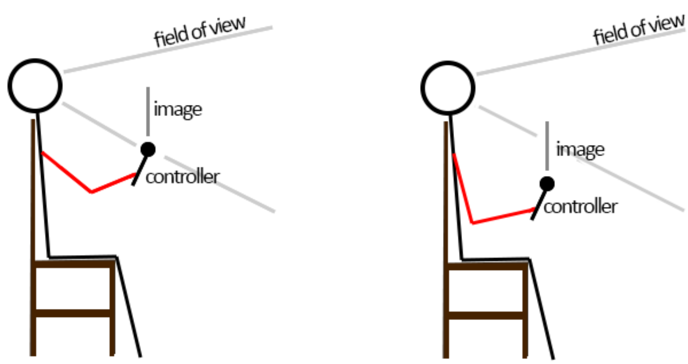

Figure 29: Different ways for holding the Vive that affected distance preference

It was possible to keep an image attached to a controller and navigate around the map bringing over an image of comparison for instance. Some users would use this to temporarily "save" an image. For example, one user grabbed a tiger image that he thought was cool and for the remaining scenarios for that interface would only use the other controller to view images as to keep the tiger image.

Visualization and navigation
While no significance was found in analyzing the results of the data. The interviews revealed information that gave a better understanding of why users liked and disliked certain aspects about the different interfaces.

VR Sickness
From the VR sickness results in the first study, it was clear that the park sign interface was superior with regards to VR sickness. This was reaffirmed by the second study interviews. Both the panorama (7) and the floor (10) had a

significant number of people indicate that they experienced some form of nausea in those interfaces. According to the participants, for the panorama this was primarily because of the built-in rotation system whereas for the floor map this was from either rotating, looking down or a combination of the two.

Floor interface
Users that were positive about the interface called it immersive (7), fun (6), natural (4), intuitive (4) and easy to navigate (8). Users negative about the interface said they were unable to get a good overview of the map (5) and the images were obstructing the view making it hard to navigate (2). When there were a lot of images, users could get surrounded by the images and this could be perceived as either a great and engaging way to view images or an overwhelming (negative) experience. Only two users mentioned immersion for the panorama interface and none for the park sign interface.

Panorama interface
Users that were positive about the interface ascribed the following keywords to it: good overview (6), easy (4), continuous (surrounding the user seen as positive) (8) and intuitive (8). Negative keywords for the panorama interface mostly involved that rotation was making it slower than the park sign interface and that the overview was bad (5).

Park sign interface
The park sign interface was given the positive keywords of good overview (9), fast (4), easy (3), and negative keywords such as boring (3) and having bad viewing angles (3). Users preferring the park sign interface usually did so because it was the fastest interface to navigate for them. Zooming out the users can see the entirety of the map and using teleportation be anywhere in an instant. Because this is the most common visualization for maps using other media it was also seen as boring.

Navigation
Remarks specifically about the navigation showed that users that preferred the teleportation over the flying navigation (11) choose this predominantly because teleportation is much faster, more intuitive and easier to use. Users that preferred flying found it more immersive, fun and gave much more control. As navigating through teleportation required a new teleportation for short distances and for small errors, flying was generally seen as more suited for close navigation whereas teleportation was seen more suited for long distance navigation.

Usefulness and personal use The second question of the interview was related to personal usage. Provided that users had a VR headset, a computer that was capable of running it and they could make modifications to the dataset and/or the map allowing for zooming, local maps and different map visualizations (colors, information etc.), would they use any of the interfaces? If yes for what purpose and if no why not? Out of all the participants only one participant indicated that he would not use the interface for any purpose as looking at images is not in his interest. The responses from the other participants are listed below:

Planning a vacation
Out of the 35 participants, 23 users said that they would use this software to help plan their vacations. Different parts of vacation planning came forward such as comparing multiple destinations, getting a good idea of the surrounding places/attractions to visit as well as discovering new destinations to go to. One user would make photo collages of what she wanted to visit before going on a holiday and was interested in using this program to do that with.

Route planning
Three users would use it for route planning. One user would often get lost using normal maps and wanted to have a idea visually of how to travel and the interface would be useful to her for this purpose. The other two users enjoyed making scenic road trips and would use the interface to find out which route was more enjoyable to drive to a certain destination.

Discovery exploration as entertainment
Six users were interested in using it for entertainment purposes and would like to look at images on a map at a variety of topics such as: nature, landmarks, visually pleasing images, cultures, Unesco heritage sites, amusement park, food, architecture, fishing locations, aerial photos, football stadiums and food.

Self learning or as educational teaching tool
Three users would use it for self learning about different interests, including political and historical development of areas over time. One user was a geography teacher and wanted to use the system as a teaching tool for his geography lessons.

Rewatching own holiday photos
Eighteen users would look at their own holiday images on a map. Out of the eighteen users, eight came up with this idea and ten users would find that interesting after it was suggested to them that they could use their own image data on the map. One user was specifically fond of making panorama shots when on holidays which is well supported by VR. While four users did not like watching their own holiday images, they did see appeal in using VR to show their holiday images to friends and family using the interface.

Additional remarks
As mentioned before, pin clustering is an issue when it comes to visually placing data according to spatial location on a map when there is a lot of overlap in terms of location. A third of the users mentioned specifically that this was a problem for them in the landmark scenario where multiple images could overlap making it harder to find the specific landmark they were looking for. While it

was clear that this could be a potential problem for users, this was not within the scope of this research. Several users also expressed that they would not only like to browse images in VR on maps but videos as well.

5.6.4 Performance measures

As the scenarios performed by the users are affected by the interest users have in the topics pertaining to the images, for both the exploration and the comparison scenarios the use of the performance data is very limited. Judging by the averages listed below (table 3) we can see that users spend more time on the floor interface which could be attributed to it using flying for navigation which for long distances is slower than teleportation.

Interface	Average time	Standard deviation
Floor	10:17:31	02:32:40
Panorama	09:23:41	02:45:04
Park sign	09:57:22	02:51:01

Table 3: performance measures

However for the task of finding landmarks the performance measures give an indication of the potential speed with regards to "lookup" type searches (table 4).

Performance measure results regarding landmark scenario	
Average	1 minute 18 seconds
Standard deviation	54 seconds

Table 4: user performance for landmark

The fastest lookup search was completed in 10 seconds, with the longest taking 4 minutes and 45 seconds where the user was dedicated to find the specific landmark in a cluster of images.

5.7 Discussion

The purpose of the study was to get a better understanding and insight into effective ways of browsing images in VR using geospatial maps. The primary aspects and the scope of the research was to research the effectiveness in terms of user experience for both the visualizations and the accommodating navigations.

Using the USE questionnaire we were unable to find significance. While no significance was found, all categories of the USE questionnaire for each visualization had high scores with a combined average scores of 5.900 (park sign), 5.977 (panorama) and 5.61 (floor) and each category almost exclusively above 5.5 (figure 25).

As the USE questionnaire was scored using a 7-point Likert scale with scores ranging from one to seven, these results indicate that users agree that the interfaces are all useful, easy to use, easy to learn and give the users a satisfying experience. Because of this all three visualizations are deemed viable options when used for geospatial image browsing using VR and the interview data outlines some differences between the visualizations that can aid in the understanding of their benefits and drawbacks. However, the floor interface seemed to be associated the most with fun and immersion. Therefore, it seems that for the purposes of image browsing as entertainment and a leisure activity this is the better choice out of the three.

Landmark scenario performance data showed that the map interface also has the potential for search tasks. While the focus of the study was not performance, most users were able to complete the task in under a minute. Here we do note that the performance was negatively affected by the real-time loading of images from the Flickr database as at several occasions during testing, participants had to wait up to ten seconds before the images appeared.

When accounting for the search tasks, perhaps the best choice is the park sign interface. Being most comparable to the 2D standard from other devices this interface is considered fast and easy with a good overview while also being found boring. It has the lowest VR sickness and is thus also the safest option. The panorama interface was also considered to have a good overview and easy to use and understand, like the park sign interface but slightly slower due to the need for rotation. The biggest contention between the park sign and the panorama seems to be based on the mental map model that each individual has of the earth. Users preferring the panorama over the park sign stated that the world being a sphere it made sense to them that they could navigate a continuous map. Users positive of the park sign visualization stated that this was because in the panorama interface a part of the map was always behind them and thus a good overview of the entire map was not possible. Instead they had a hard time orienting themselves. Observations of these users often showed that their mental map model was flat. During a scenario, users were asked to visit both Mexico and Japan. When travelling from one to the other users would rotate according to the flat equirectangular projection map travelling across the Atlantic Ocean, past Europe Africa and most of Asia rather than the short distance across the Pacific Ocean.

6 Conclusion

We have presented a system for image browsing on geographical maps in virtual reality using 3D head mounted displays. This system comes with two modes of navigation (flying and teleportation) and three modes of visualization (park sign, floor and panorama) and has been tested using two comparative studies.

The first study focused on evaluating both navigations for each individual visualization. The results concluded that teleportation was more effective for both the park sign and the panorama visualization. For the floor map both visualizations could be used.

The second study was conducted on evaluating three combinations selected based on the results from the first study. It compared the combinations for user experience with image browsing and the data from the conducted interviews can contribute to understand and improve aspects for future research. The scores given by participants showed promising results for leisure and exploratory browsing for all three combinations.

During the research for our system, it was already adopted and used by K. Ouwehand for research pertaining to the visualization of lifelogging data.

7 Future work

The topic of our research, geospatial image browsing in VR, is multifaceted and as such it has many aspects and open areas for future research. VR itself already has made large technological improvements in the past decade. Aside from improving the existing technology, making it faster, more accurate and improving the visual quality, new ways of interacting with the virtual environment are still being created that could be noteworthy for the system we created.

As it is the most common way for users to do leisure image browsing, we chose to limit our research to a seated position with a non-rotary chair. Because of this our system is feasible in almost all circumstances and requires no additional hardware other than a chair or a couch. As such, we have automatically excluded a variety of ways to use VR for navigation. Set-ups involving physical walking do require a sizeable physical area of free space, or other physical hardware such as a VR treadmill, but has the potential for an even more immersive experience. Therefore these are areas for future research to explore.

For our navigation we used two established methods, flying and teleportation, to navigate the VR space. As shown in the interviews, users felt successful using these methods for their exploratory search but acknowledged each had their own strengths and weaknesses. These two navigations combined could prove to be even more effective at navigating our system as it would effectively negate the drawbacks of both methods. However, further research would be needed to confirm this.

With regards to visualization we created three intuitive visualizations for our research, but in our initial development we had two other promising visualizations that were not introduced in our study. These visualizations were both spherical, with the user either being outside or inside the sphere similar to the exocentric and egocentric globe visualizations as used by Yang et al [37]. Our system was designed as a tile based structure. To make the spherical visualizations have the same visual representation while not having any distortion and keeping the geographical coordinates accurate would have required additional time and resources to create a custom set of map tiles for multiple projections. Because the research time per participant was already estimated to take an hour each with three visualizations, the two spherical interfaces excluded from the study. Even with these two included, the list of possible visualizations for VR is certainly not exhaustive and there are more visualizations that can be explored during future work.

Additionally, there is the problem of handling large datasets in image browsing. This is a large problem in general that has many approaches and for our research we considered this outside of its scope. As mentioned by many participants, images or pins clustered too closely together could make it difficult to see both the map and images. There are many ways this problem can be approached. Firstly, new tools for filtering can be introduced so that the user can filter by keywords or metadata such as datetime and color. This would reduce the number of pins at locations and gives the user ways to adjust the dataset to better suit their search both for exploratory and lookup scenarios. As our system is tile based using tiles from OpenStreetMaps, it is suitable to extend both local maps, or zooming by allowing the user to increase the level of detail on tiles by subdividing them into tiles of a higher zoom level. As VR headsets give the user a perspective view rather than the general 2D isometric view, there are different ways to achieve zooming. For our cylindrical interface and especially if one would implement spherical interfaces, this is not as straightforward as in 2D. Displaying the map markers can also be done differently to alleviate this problem by combining markers on certain locations such as an isopleth map or using larger markers to represent the presence of multiple markers and researching how best to interact with those markers in VR.

Last of all, our system uses flat tiles to represent the map. Using heightmaps or physically deforming the map, especially on the floor map, using heightmaps or other 3-dimensional coordinate systems could benefit the user with navigating the map by making it more closely representative of its real world counterpart. While this is technically not limited to VR, it could be beneficial to the immersion of the user and thus making VR a very suitable platform.

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A USE original

Usefulness

1. It helps me be more effective.
2. It helps me be more productive.
3. It is useful.
4. It gives me more control over the activities in my life.
5. It makes the things I want to accomplish easier to get done.
6. It saves me time when I use it.
7. It meets my needs.
8. It does everything I would expect it to do.

Ease of use

1. It is easy to use.
2. It is simple to use.
3. It is user friendly.
4. It requires the fewest steps possible to accomplish what I want to do with it.
5. It is flexible.
6. Using it is effortless.
7. I can use it without written instructions.
8. I don't notice any inconsistencies as I use it.
9. Both occasional and regular users would like it.
10. I can recover from mistakes quickly and easily.
11. I can use it successfully every time.

Ease of learning

1. I learned to use it quickly.
2. I easily remember how to use it.
3. It is easy to learn to use it.
4. I quickly became skillful with it.

Satisfaction

1. I am satisfied with it.
2. I would recommend it to a friend.
3. It is fun to use.
4. It works the way I want it to work.
5. It is wonderful.
6. I feel I need to have it.
7. It is pleasant to use.

B USE first study

Usefulness

1. It is a useful way for completing the task
2. It helps me be more effective in completing the task
3. It meets my needs for navigating the map
4. It does everything I would expect it to do

Ease of use

1. It is easy to use
2. It is simple to use
3. It is user friendly
4. It requires the fewest steps possible to accomplish what i want to do with it
5. It is flexible
6. Using it is effortless
7. I can use it without written instruction
8. I don't notice any inconsistencies as I use it
9. Both occasional and regular users would like it
10. I can recover from mistakes quickly and easily
11. I can use it successfully every time

Ease of Learning

1. I learned to use it quickly
2. I easily remember how to use it
3. It is easy to learn to use it

Satisfaction

1. I am satisfied with it
2. It is fun to use
3. It works the way I want it to work
4. It is pleasant to use

C USE second study

Usefulness

1. This map visualization is useful to me
2. This map navigation is useful to me
3. This map is useful for finding locations quickly
4. It makes it easy to accomplish what i want to do
5. It does everything I expect it to do

Ease of use

1. It is easy to use
2. It is simple to use
3. It is user friendly
4. It requires the fewest steps possible to accomplish what i want to do with it
5. It is flexible
6. Using it is effortless
7. I can use it without written instruction
8. I don't notice any inconsistencies as I use it
9. Both occasional and regular users would like it
10. I can recover from mistakes quickly and easily
11. I can use it successfully every time

Ease of learning

1. I learned to use it quickly
2. I easily remember how to use it
3. It is easy to learn to use it
4. I quickly became skillful with it

Satisfaction

1. I am satisfied with it
2. It is fun to use
3. It works the way I want it to work
4. I feel more engaged with the system
5. I feel more engaged with the images
6. It is pleasant to use

D Consent Form

Risks, Discomforts and Benefits
Be aware that when using virtual reality systems, some people may experience some degrees of the following: Nausea, Vomiting, Sweating, Pallor, Headache, Vertigo and/or Dizziness

Furthermore using VR applications and games have the possibility of creating epileptic episodes, therefore people who are known to have suffered from epilepsy are not allowed to volunteer.

Upon request, testing will be immediately terminated or if there are indications that the discomfort becomes unbearable or abnormal responses occur. Participation in this study should be an interesting and enjoyable experience and the results obtained are expected to assist computer science research.

Confidentiality
Any information that is shared during the study will be treated strictly confidential and once the study is completed, it will not be possible to identify individuals. Throughout the study only the aforementioned researchers will have access to the information.
Request for Further Information
You are encourage to discuss any concerns regarding the study with the testing researcher at any time, and to ask any questions that you might have.

Refusal or Withdrawal
You may refuse to participate in the study and if you do consent to participate then you will be free to withdraw from the study at any time without consequence, fear or prejudice. If you wish to withdraw from the event please contact the researcher and all data pertaining to you will be destroyed.

I have read the information above	YES/NO
I have had the opportunity to ask questions about the procedure	YES/NO
All my questions were answered to my satisfaction	YES/NO
I have received sufficient information about the study	YES/NO
I understand and accept the risks associated with the use of virtual reality	YES/NO
I consent to the audiotaping of the experiment	YES/NO
I certify to have no history of epilepsy	YES/NO
Name	
Date	
Signature	

E VRSQ questionnaire

VRSQ symptom	Oculomotor	Disorientation
1. General discomfort	O	
2. Fatigue	O	
3. Eyestrain	O	
4. Difficulty focusing	O	
5. Headache		O
6. Fullness of head		O
7. Blurred vision		O
8. Dizzy (eyes closed)		O
9. Vertigo		O
Total	1	2

F Scenarios second study

Explore	Explore images of sports and activities in South East Asia. Countries like Malaysia, Brunei, the Philippines, Indonesia, Singapore and Thailand to see what physical activities people enjoy there.
Compare	Assume you like going for nature walks and tours on your holiday. Compare images from the West and East coast of the United States to see where you would rather go
Geospatial knowledge	Find a user specified landmark

Explore	Explore images of the people or brazil to get a better understanding of their culture and their activities
Compare	Let's say you can go to a restaurant tonight to order authentic food from either Brazil and India, explore the food images of these countries to see which option would be more appealing to you
Geospatial knowledge	Find a user specified landmark

Explore	Assume you are a food lover and want to get an idea of what type of cuisines they have in Japan
Compare	Imagine you like looking at beautiful landscapes, inspect the landscape images in Mexico and Japan and see which country you think has more appealing landscapes.
Geospatial knowledge	Find a user specified landmark

Explore	Explore images of architecture in Italy to get an understanding of how their buildings and infrastructure looks
Compare	Imagine you would receive an arrangement of flowers, and you had to choose between an arrangement of native Mexican flowers, or native Brazilian flowers. Based on the images of flowers at these respective countries, from which country would you prefer the flowers are from?
Geospatial knowledge	Find a user specified landmark

Explore	Assume you are a food lover and want to get an idea of what type of cuisines they have in South East Asia. Countries like Malaysia, Brunei, the Philippines, Indonesia, Singapore and Thailand
Compare	Assume you like going for nature walks and tours on your holiday. Compare images in New Zealand and India to see which country you would rather go to
Geospatial knowledge	Find a user specified landmark

Explore	Explore images of architecture in New Zealand to get an understanding of how their buildings and infrastructure looks
Compare	Assume you like going for nature walks and tours on your holiday. Compare images in Spain to see where you would rather go
Geospatial knowledge	Find a user specified landmark

G Results VRSQ first study

VR Sickness Data Overview		
Combination	Average	Variance
Park Sign Fly	16.89	15.58
Park Sign TP	13.08	12.84
Panorama Fly	19.86	17.34
Panorama TP	17.21	15.24
Floor Fly	19.09	18.23
Floor TP	22.10	17.63

Table 6: VRSQ average and standard deviation

VRSQ	Park Sign		Panorama		Floor	
	Flying	Teleportation	Flying	Teleportation	Flying	Teleportation
Mean	16.88405797	13.07971015	19.85507246	17.21014493	19.0942029	22.10144928
Variance	242.8798858	164.863307	300.7987484	232.1722661	332.4440053	310.9134826
Observations	23	23	23	23	23	23
Pearson Correlation	0.827978828		0.92004587		0.658615072	
Hypothesized Mean Difference	0		0		0	
df	22		22		22	
t Stat	2.087662313		1.856271581		-0.972635338	
P(T<=t) one-tail	0.024310905		0.038429373		0.170654038	
t Critical one-tail	1.717144374		1.717144374		1.717144374	
P(T<=t) two-tail	0.048621809		0.076858747		0.341308077	
t Critical two-tail	2.073873068		2.073873068		2.073873068	

H Results USE first study

Sign map	Flying		Teleportation	
	Mean	Variance	Mean	Variance
Usefulness	5.271739	1.306324	6.141304	0.686512
Ease of use	5.237154	1.626401	5.86166	0.691112
Ease of learning	5.927536	0.817743	6.333333	0.505051
Satisfaction	5.326087	1.809289	6.119565	1.073123

Panorama	Flying		Teleportation	
	Mean	Variance	Mean	Variance
Usefulness	4.84375	1.748981	5.864583	0.505322
Ease of use	5.068182	1.096119	5.75	0.634028
Ease of learning	5.75	1.152174	6.166667	0.541063
Satisfaction	4.895833	2.646286	5.885417	0.760756

Floor	Flying		Teleportation	
	Mean	Variance	Mean	Variance
Usefulness	5.52	1.207917	4.97	2.095417
Ease of use	5.509091	0.940083	5.083636	1.643196
Ease of learning	5.946667	0.487778	5.746667	0.937778
Satisfaction	5.65	1.786458	5	3.265625

Park Sign	Usefullness		Ease of Use		Ease of Learning		Satisfaction	
	Flying	Teleportation	Flying	Teleportation	Flying	Teleportation	Flying	Teleportation
Mean	5.271739	6.141304	5.237154	5.86166	5.927536	6.333333	5.326087	6.119565
Variance	1.306324	0.686512	1.626401	0.691112	0.817743	0.505051	1.809289	1.073123
Observations	23	23	23	23	23	23	23	23
Pearson Correlation	0.386597		0.430969		0.141459		0.464142	
Hypothesized Mean Difference	0		0		0		0	
df	22		22		22		22	
t Stat	-3.71427		-2.52793		-1.82194		-3.01888	
P(T<=t) one-tail	0.000604		0.00958		0.041044		0.003156	
t Critical one-tail	1.717144		1.717144		1.717144		1.717144	
P(T<=t) two-tail	0.001208		0.019159		0.082088		0.006312	
t Critical two-tail	2.073873		2.073873		2.073873		2.073873	

Panorama	Usefullness		Ease of Use		Ease of Learning		Satisfaction	
	Flying	Teleportation	Flying	Teleportation	Flying	Teleportation	Flying	Teleportation
Mean	4.84375	5.864583	5.068182	5.75	5.75	6.166667	4.895833	5.885417
Variance	1.748981	0.505322	1.096119	0.634028	1.152174	0.541063	2.646286	0.760756
Observations	24	24	24	24	24	24	24	24
Pearson Correlation	0.300253		0.394173		0.263097		0.303397	
Hypothesized Mean Difference	0		0		0		0	
df	23		23		23		23	
t Stat	-3.84722		-3.22467		-1.80579		-3.03824	
P(T<=t) one-tail	0.000411		0.001875		0.042029		0.00292	
t Critical one-tail	1.713872		1.713872		1.713872		1.713872	
P(T<=t) two-tail	0.000822		0.003751		0.084058		0.005841	
t Critical two-tail	2.068658		2.068658		2.068658		2.068658	

Floor	Usefullness		Ease of Use		Ease of Learning		Satisfaction	
	Flying	Teleportation	Flying	Teleportation	Flying	Teleportation	Flying	Teleportation
Mean	5.52	4.97	5.509091	5.083636	5.946667	5.746667	5.65	5
Variance	1.207917	2.095417	0.940083	1.643196	0.487778	0.937778	1.786458	3.265625
Observations	25	25	25	25	25	25	25	25
Pearson Correlation	0.0806		0.308425		0.170856		0.215635	
Hypothesized Mean Difference	0		0		0		0	
df	24		24		24		24	
t Stat	1.575453		1.578309		0.914991		1.622888	
P(T<=t) one-tail	0.064122		0.063793		0.184649		0.058839	
t Critical one-tail	1.710882		1.710882		1.710882		1.710882	
P(T<=t) two-tail	0.128243		0.127586		0.369298		0.117677	
t Critical two-tail	2.063899		2.063899		2.063899		2.063899	

I Results USE second study

Measure: Usefullness						
(I) UX	(J) UX	Mean Difference (I-J)	Std. Error	Sig.a	95% Confidence Interval	
					Lower Bound	Upper Bound
Park Sign	Panorama	-0.129	0.15	1	-0.507	0.249
	Floor	0.424	0.25	0.299	-0.207	1.054
Panorama	Park Sign	0.129	0.15	1	-0.249	0.507
	Floor	0.553	0.225	0.058	-0.015	1.121
Floor	Park Sign	-0.424	0.25	0.299	-1.054	0.207
	Panorama	-0.553	0.225	0.058	-1.121	0.015

Measure: Ease Of Use						
(I) UX	(J) UX	Mean Difference (I-J)	Std. Error	Sig.a	95% Confidence Interval	
					Lower Bound	Upper Bound
Park Sign	Panorama	0.032	0.135	1	-0.309	0.374
	Floor	0.294	0.189	0.387	-0.182	0.77
Panorama	Park Sign	-0.032	0.135	1	-0.374	0.309
	Floor	0.262	0.159	0.329	-0.14	0.664
Floor	Park Sign	-0.294	0.189	0.387	-0.77	0.182
	Panorama	-0.262	0.159	0.329	-0.664	0.14

Measure: Ease Of Learning						
(I) UX	(J) UX	Mean Difference (I-J)	Std. Error	Sig.a	95% Confidence Interval	
					Lower Bound	Upper Bound
Park Sign	Panorama	-0.022	0.107	1	-0.291	0.247
	Floor	0.206	0.171	0.709	-0.225	0.636
Panorama	Park Sign	0.022	0.107	1	-0.247	0.291
	Floor	0.228	0.153	0.435	-0.157	0.613
Floor	Park Sign	-0.206	0.171	0.709	-0.636	0.225
	Panorama	-0.228	0.153	0.435	-0.613	0.157

Measure: Satisfaction						
(I) UX	(J) UX	Mean Difference (I-J)	Std. Error	Sig.a	95% Confidence Interval	
					Lower Bound	Upper Bound
Park Sign	Panorama	-0.188	0.166	0.792	-0.606	0.23
	Floor	0.212	0.285	1	-0.507	0.931
Panorama	Park Sign	0.188	0.166	0.792	-0.23	0.606
	Floor	0.4	0.236	0.3	-0.196	0.996
Floor	Park Sign	-0.212	0.285	1	-0.931	0.507
	Panorama	-0.4	0.236	0.3	-0.996	0.196