FACULTY OF SCIENCE
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Master's Thesis

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Proximity-based Multi-scale Navigation

For Large Wall Displays

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December 14, 2012

ABSTRACT

Large wall size displays offer opportunity for interacting with large datasets, which can't normally fit to desktop sized displays. While interaction with such displays and mid-air pointing techniques has been broadly studied, high-level complex tasks such as multi-scale navigation and zoom+pan interfaces have received little attention.

The objective of this thesis project is three fold; (1) To design and implement zoomable user interface (zoom+˙pan) using existing APIs for wall-sized display, (2) to couple embodied resources and bodily movement to multi-scale navigation via designing and implementing bodily(movement) based navigation techniques (3) to evaluate the designed navigation techniques by conducting user studies and controlled experiment.

ACKNOWLEDGMENTS

This thesis would not have been possible without the guidance and help of several individuals who in one way or another contributed in preparation and completion of this study.

First and foremost, my deepest gratitude goes to my supervisor Kasper Hornbæk for providing me invaluable assistance and guidance throughout the thesis period. I would like to thank Mikkel Jacobsen, Anders Markusen and Soren Knudsen for their valuable assistance and support. I would also like to thank participants of the user studies and experiments for spending hours and providing invaluable comments.

Last but not least, I would like to thank my families and friends for providing great encouragements. My special gratitude goes to my sister Rahel Sahlemariam, for priceless advices and countless support throughout the study.

CONTENTS

CHAPTER 1 - INTRODUCTION

Very high resolution wall displays opens up a new opportunity for interacting with large datasets. They are proved to accommodate hundreds of megapixels and make it possible to visualize different datasets from various research domains. As display size increases, a number of researches have been made, ranging from prototype applications, optimization of existing interaction and pointing techniques and various empirical studies on interaction techniques for multi-scale navigation on wall displays. Various research works such as [41] and North and colleagues [3, 12, 13, 51, and 53] have hypothesized and later empirically proved the importance of display size in task performance for spatial tasks.

Some of the factors behind significant performance improvement in this kind of interaction setting are the use of embodied resources such as spatial memory, motor memory, peripheral vision and the opportunity to use physical navigation [13]. Physical navigation on the other hand seemed to be the key factor in task performance compared to peripheral vision [12], and significantly outperform virtual navigation from experiments such as [3, 12].

Since physical navigation benefits from perception and visual aggregation, it outperforms virtual navigation for visualization intensive spatial tasks such as pattern finding [3, 12]. However, virtual navigation is still required as datasets can be several orders of magnitude and are too large to fit on large wall displays. Therefore, research works on multi-scale navigation for wall displays should consider varies opportunities to link embodied resources, movement and multi-scale navigation in a seamless fashion.

OBJECTIVE

The objective of this thesis project is three fold:

1. To design and implement a zoomable user interface (zoom+˙pan) using existing APIs for wall displays.
2. To couple embodied resources, movement and proximity information to multi-scale navigation on wall displays via designing and implementing bodily (movement) based navigation techniques.
3. To evaluate the designed navigation techniques by conducting empirical studies, suggest possible improvements and direct to potential future works.

CHAPTER 2 - RELATED WORKS

INTRODUCTION

Large wall size displays offer opportunity for interacting with large datasets, which can't normally fit to desktop sized displays. While interaction with such displays and mid-air pointing techniques has been broadly studied, high-level complex tasks such as multi-scale navigation and zoom+pan interfaces have received little attention.

The objective of this thesis project is three fold; (1) To design and implement zoomable user interface (zoom+˙pan) using existing APIs for wall-sized display, (2) to couple embodied resources, movement and proximity information to multi-scale navigation via designing and implementing bodily(movement) based navigation techniques (3) to evaluate the designed navigation techniques by conducting user studies and controlled experiment.

Since this project is at the intersection of many HCI research areas, a brief overview of related works on visualization on large displays, mid-air interaction techniques and multi-scale navigation is discussed in this chapter.

LARGE DISPLAYS

Large displays has been used for a number of applications such as visualization of slippy map tiles (such as openstreetmap [39]), visualization and analysis of heterogeneous datasets[51], visualization of 4.7 Giga pixels of our galaxy image [19] and so on. It has been a focus of many researches and empirical studies. Much of studies and experiments conducted on large displays suggest their benefits over their smaller counterparts.

Productivity benefit

Czerwinski et al [52] presented a study investigating the productivity benefits of large tiled displays over smaller single-panel displays. They setup a 42" tiled display and a 15" display. They evaluate 15 subjects with tasks such as searching the web, coping and pasting documents across windows. They conclude that, using large displays participants became significantly more productive and more satisfied when carrying out complex multiple window tasks.

Physical navigation and peripheral vision

Ball et al [17] identified the potential advantage of using physical navigation on large displays in performing tasks on finely detailed data. They presented an exploratory study on the effects of a large tiled display with a resolution of 3840x3072 as compared to two smaller displays 1580x2048 and 1280x1024. They have conclude that higher resolution display that uses physical navigation significantly outperform smaller displays using zoom+pan interface for finely detailed data.

On another research work Ball et al [53] conducted experiments to find out how to maximize the effectiveness of details-on-demand interaction technique with large displays and map applications. They reported that for spatial tasks such as route tracing in maps, nine monitor condition (the largest display) resulted improvement on average task completion time. They have also monitored mouse clicks on the experiment conditions, and found out that using large display resulted 70% reduction on mouse clicks.

Ball et al [12] conducted a controlled experiment to evaluate the usability and user preference of display size and performance evaluation for each display size conditions. They designed a zoom+pan interface (with static basemap and semantic dataset) and created four spatial tasks (search, navigation, pattern finding tasks and insight tasks). They have also monitored amount of physical and virtual navigation in performing experiment tasks. They found out that virtual navigation having negative effect on task performance. They reported that as display size increased, virtual navigation decreased, and performance time also decreased. They have also reported that participants preferred in doing physical navigation over virtual navigation to complete those tasks.

On a follow-up study Ball et al [13] related space-scale model and navigation techniques (physical and virtual) as a theoretical link between embodied interaction and visualization. The augmented space-scale model helped to include the idea of change in viewport size and the idea of a difference in behaviors between virtual and physical navigation. They have conducted an experiment to find out how performance, physical navigation and virtual navigation are affected by different display sizes. They setup 24 17" LCD displays in an 8x3 matrix, and divided the visualization into 3 display-size conditions, 1-column, 4-column and 8-column conditions. The visualization is similar to their earlier work [12], static basemap with semantic dataset. For virtual navigation, Gyroscopic mouse is used which is again used to manipulate experiment tasks. They reported that physical navigation is preferred over virtual navigation in 100%, 32 out of 32 participants. They also found a correlation between virtual navigation and performance with a correlation coefficient of 0.69 and 0.68 for number of zooms and pans, respectively. This indicates that based on their experiment setup and task specifics, virtual navigation resulted in higher task completion time. However, one should note that virtual navigation discussed in this context refers to virtual navigation of space-scale using a mouse. The other interesting finding from this empirical study was related to the importance of the design of semantic zooming and that semantic zooming threshold affects performance. They stated that:

> "…*zooming requires computational power and time and disorients people (by not having an optical flow), both of which hurts performance time. Larger displays were able to mitigate some of these problems by broadening the view beyond initial semantic thresholds*".

If insufficient details were presented then zooming-in is required and if too much detail were presented then zooming-out is required. However, one should note the necessity of virtual navigation since it cannot be possible to fit large sized datasets (such as openstreetmap tiles) to a display for physical navigation.

A number of research works indicated that as display size increases so do performance and user satisfactions. This might be from the availability of wider field of view and extended peripheral vision, or from the use of physical navigation. Ball et al [3] conducted an experiment with sole purpose of finding the actual reason behind performance improvement. They made an empirical study with two conditions by designing specific display setup for physical and peripheral conditions. They have used a static basemap and semantic dataset and created spatial tasks. They have found out that physical navigation as a more critical factor to the performance improvement for most of spatial tasks (search, compare, navigation) than increased field of view. However, they also discussed that peripheral vision resulted in minor performance improvement for pattern finding task.

Display curvature

Shupp et al [55] have conducted an experiment to evaluate user performance, accuracy and mental workload on multi-scale geospatial tasks (search, route tracing and comparison). They also designed experiment condition to determine if the curvature of large displays affects performance. For this experiment they setup a separate condition for display size and display curvature by preparing tiled displays of size 4x3 and 8x3. From their analysis, no significant interaction effect was found between display curvature and display size. However, display size – task type interaction was found. This indicates that display curvature contributed to task performance regardless of display size.

In summary large displays bring opportunity for physical navigation, wider field of view thereby utilizing peripheral vision, encourage better utilization of embodied resources such as spatial memory, motor memory and optical flow. Therefore, navigation techniques for such interaction space should be designed in such a way that maximizes the utilization of embodied resources and physical navigation. For further reference on large displays, technical design and large scale visualizations please refer Tao et al [54].

MID-AIR INTERACTION TECHNIQUES

Pointing and interaction on mid-air has been studied for couple of years for immersive virtual environments, 3D user interfaces and information space on large wall-displays.

On their earlier works Shoemaker et al [55] have designed an interaction technique by using perspective projection of user's shadow as a link between personal and extra-personal space [56]. The main objective of their work was to provide fluid access to all areas of the large display for a single user and providing awareness of interactions to collaborators. They have prototyped three mockup applications; single point shadow reaching interaction, whole body interaction and shadows as magic lenses, figure-2.1.

Figure-2.1, shadow reaching and magic lenses shadow mockups, image taken from Shoemaker et al [55]

On their recent work Shoemaker et al [57] presented a body-centric interaction for wall displays. They have used geometric human model with orthographic projection, which interactively updated from user pose thereby reflecting awareness for single person as well as collaborative tasks. They made a prototype map viewing application and used two Nintendo Wiimote controllers to provide pointing and clicking capability.

Nancel et al [19] conducted a controlled experiment to evaluate factors for the design of mid-air multi-scale navigation (zoom+pan interface). They created conditions for three factors; uni vs. bimanual interaction, linear vs. circular and level of guidance to perform gesture in mid-air. From their experiment, bimanual interaction, linear gesture and high level of gestural guidance resulted significant performance improvements.

Marquardt et al [16] on the other hand, used user's position and orientation information (proxemics) to interact with smart and trackable devices such as cellphone, a trackable wand and large display. They also design a prototype application with shared interaction space as shown in figure2.2. Figure-2.2 shows a media player which changes the displayed information appropriate to the proximity of viewers

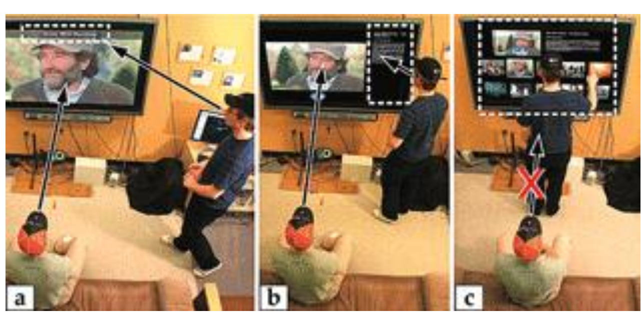

Figure-22, a media player which changes content appropriate to proximity of users

MULTI-SCALE VISUALIZATION INTERFACES

Much research work has been made on navigation techniques and multi-scale interfaces on desktop displays, however little research has been made on large wall displays.

Earlier works of Baudisch et al [59 and 60] introduced focus plus context visualization techniques by integrating high resolution screen (focus) into a low resolution projector based display (context). They hypothesized and latter empirically proved that focus+context resulted in less task completion for map tasks [60].

As part of the evaluation task performance for navigation factors on mid-air multi-scale navigation, Nancel et al [19] have adopted Fitts' reciprocal pointing task for zoom+pan interface they built for large wall displays.

Jakobsen et al [61] conducted an empirical study to find out the effect of display size and multi-scale interfaces by creating three spatial tasks (navigation, tracing and comparing). They found out that interactive visualization techniques worked best for medium and large display size in term of task completion time. They also reported that overview+detail outperform the other interfaces for all display size conditions, in particular for comparing tasks.

Although there are different multi-scale interfaces, zoom+pan interface is used in this thesis project. However, studying the effect of multi-scale visualization interfaces on large displays can be a potential future research work and empirical studies. For more information on different multi-scale interfaces, please refer a survey of Cockburn et al [58].

CHAPTER 3 - USER TRACKING AND DESIGNING ZOOM+PAN INTERFACE

In this chapter the process of designing zoom+pan interface for wall display is discussed. To design movement based navigation techniques for multi-scale (zoom+pan) interface on wall displays, a variety of projects, opensource as well as proprietary software was used. User's gaze position was first calculated from the raw position and rotation quaternion from the tracker. Head gaze point was then used as movement feedback for manipulating virtual camera based on the different navigation techniques (Gaze, Absolute and Relative navigation techniques, as discussed in chapter-5). In the subsequent sections various methods for tracking users on controlled as well as uncontrolled environment is discussed. Gaze estimation and the overall system architecture of zoom+pan interface is also presented.

USER TRACKING

User tracking has been used in a number of application domains. Some of them are Augmented Reality, Games, Robotics, etc. And, a variety of tracking methods have been proposed and implemented for last few decades. We can divide user tracking techniques as indoor and outdoor. For user tracking in indoor environment, most research works are based on vision. We can again divide vision techniques into two; marker based and Markerless (natural features). For outdoor environment, there are two groups of earlier works, inertia based and GPS based approaches. Figure 3.1 shows classification of user tracking methods from earlier research works.

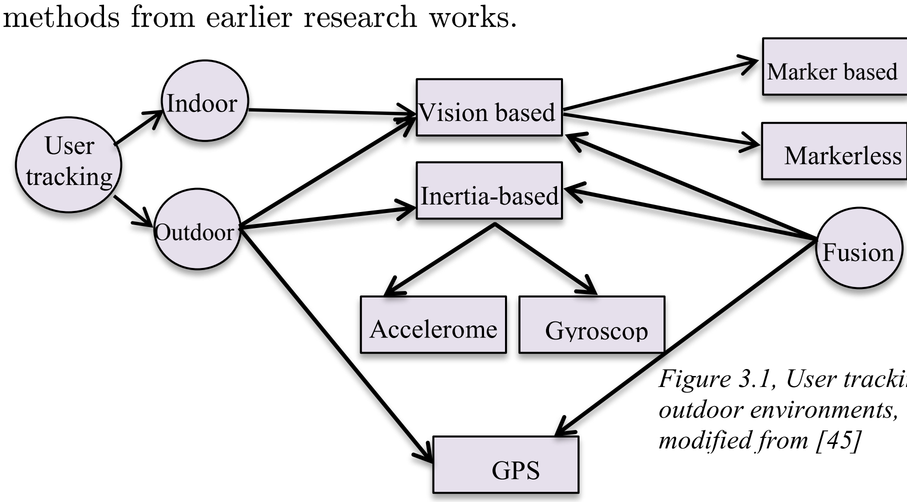

Figure 3.1, User tracking in indoor and outdoor environments, image taken and modified from [45]

USER TRACKING IN OUTDOOR ENVIRONMENTS

Unlike in Indoor environments, vision based user tracking in outdoor environment consists of a number of challenges. First, there is a difficulty in preparing the environment for tracking purpose compared to controlled environments, such as indoors. Second, the different lighting and environmental conditions will alter tracking accuracy. Moreover, pre-defined artificial markers cannot fit to user tracking in outdoor environment, instead Markerless natural features will be used, which again opens up a new challenge, high resource demanding operations such as natural feature matching and feature classification to be computed in real time. This requires high performance hardwares which are not available in most handheld devices, and creates challenge in displaying a video feed for interactive applications such as AR in interactive frame rate. To alleviate the challenges in vision based user tracking for outdoor environment, researchers have used multiple sensory devices such as GPS and inertial devices [46] in a loosely coupled system as well has tightly coupled sensor fusions [45].

GPS together with rotational information sensors such as compass was one of alternatives for position and orientation estimation of users in outdoor environments. In ARCHEOGUIDE project [46], a wearable augmented reality system was designed for outdoor exploration and Archeology. GPS has been used to provide rough estimate of user's position. Together with other sensory devices such as compass and camera, they were able to provide real time user tracking. 10-15 FPS video feed augmented with virtual objects and semantic information was displayed on the real video feed via head mounted display.

Other than using sensory devices independently or in a loosely couple system for user tracking in outdoor environment, researchers have used sensor fusion where multiple sensory devices are tightly coupled to create a unit sensor. Hol et al [47] have designed an AR framework using a combination of vision sensor (camera) and inertial sensor. They have used Inertial Measurement Unit (IMU) for acquiring position and orientation – pose – information. And a computer vision based approach to was used to alleviate inaccuracies from the inertial sensor.

USER TRACKING IN INDOOR ENVIRONMENTS

User tracking in indoor environment can be accomplished in either outside-in or inside-out approaches [48]. In inside-out approach the sensor is attached on the user and tracks artificial markers attached to the working environment. In outside-in approach sensors are attached in the environment while markers are attached on the user.

The inside-out approach

In the inside-out approach, the sensor (for example, camera), is attached on the user, and tracks annotated artificial markers from the environment. The camera basically tracks reflective markers such as infrared reflective spherical markers or it searches and matches for a particular type of patterns from fiducial markers (e.g. ARToolKit [62]). Or, there might not be any artificial markers, instead the system is designed to track natural features from indoor environments, Markerless user tracking (e.g. studierstube tracker [63]).

The outside-in approach

In the outside-in approach, the sensor (for example, camera), is attached on the environment, and tracks artificial markers annotated on the user. The camera tracks reflective markers such as infrared reflective spherical markers as in the case of optitrack [64].

For this thesis project we have used optitrack system to acquire user's head position and orientation information. From the tracker system, we found user's head position ($\vec{P}$) and orientation information ($quat$) in term of rotational quaternion. We then calculated the rotated vector as,

$$\overrightarrow{U_r} = quat * \overrightarrow{U_J}$$

Where $\overrightarrow{U_J}$ is a unit vector perpendicular to the display, and $\overrightarrow{U_r}$ is a unit vector rotated in the direction of the line of regard. Since we know display's coordinates in World Coordinate System (WCS), we can then compute the length t through straightforward linear algebra. Then position vector for the approximated gaze point ($\vec{G}$) is calculated as

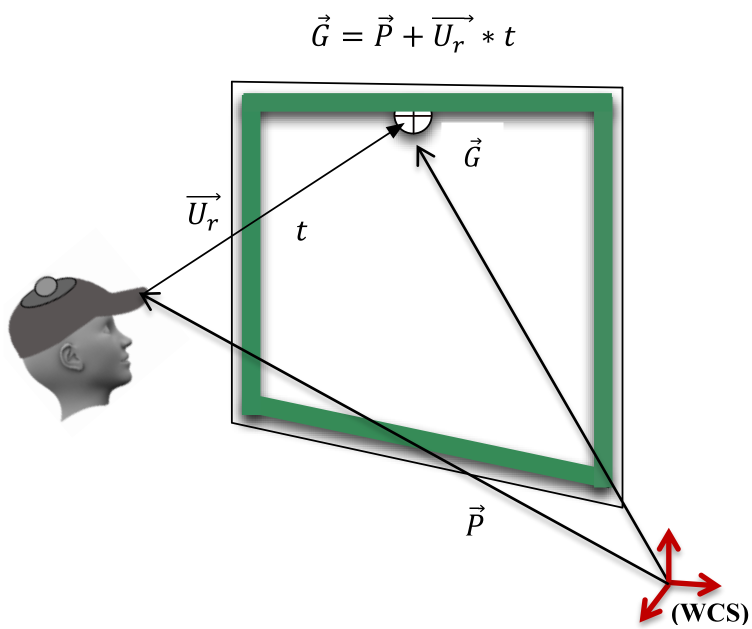

Figure 3.2, user gaze estimation from head position and orientation information

DESIGNING ZOOM+PAN INTERFACE

In designing zoom+pan interface for wall display, a number of points have been considered;

Semantic zooming capability

In some of earlier research works zoom+pan interface was made from a single static image. Zooming in such interface is magnification of basemap (static image), which leads to pixelation and artifacts after certain magnification level. On other works such as Ball et al [12], they have used static basemap with semantic information overlay. The basemap is a static image while the annotated information has various levels. This approach is much better than magnification method. However, it still uses geometric zooming. This approach can be applicable for smaller to medium sized displays. However, as display size increases so does its disadvantages.

As an initial attempt to developing zoom+pan interface with semantic zooming capability, we used openstreetmap slippy map datasets [39] and a simple GUI based on Qt framework. The approach was basically to calculate tilename (URL) for the required coordinates in the form of (l, x, y), where l is zoom level and x and y are row and column coordinate of map dataset (Mercator projection) from openstreetmap tileserver. This simple application was working in an interactive frame rate for small to medium sized displays (1920x1080 and (1680x1050). However, its performance drops as viewport size increased to 7680x3240 (3x4 projector matrix).

We then shifted to OpenSceneGraph (OSG) [36] to make use of multi-GPU rendering capability. It is also a well maintained framework with very large userbase. It makes a lot easier for graphics programming compared to the native openGL programming. For terrain rendering and dynamic LOD management we used osgEarth [40], a separate project which makes use of OSG as rendering engine.

Zoom-around Vs. Pure zoom

Zoom+pan interfaces are mostly designed with pure zooming and panning capability. In this method display center is taken as focus point for zooming operation. This means, for every zoom-in task at an arbitrary point, there is an associated panning operation. For small to medium sized displays, this approach can be applicable however, for large wall displays with movement based navigation technique, this approach obviously doesn't work. Therefore, zoom-around operations is used instead.

For bodily movement based navigation on zoom+pan interface, we make use of estimated user gaze point, figure-3.2 to align the virtual camera with various user movements.

Smooth and efficient zooming and panning

In designing zoom+pan interface, one has to consider smoothness of camera path while performing various operations. For example, to navigate from Copenhagen to Aarhus the virtual camera can only pan through space (with zoomed-in scale) and eventually rich to Aarhus. This approach obviously is not the optimal path considering the navigation time it takes. On the other hand, one can zoom-out to certain level where the two cities can be seen at the same time and perform zooming to target city.

The zoom+pan interface used for the experiment in this thesis project has a predefined bounding box around Copenhagen area. It is made as the only valid region the virtual camera can traverse through. Therefore, camera path smoothness for navigation to arbitrary point is not relevant to our context since zoom and pan operations are made as incremental and continuous approach. However, one has to note the significant importance of path smoothness for multi-scale navigation. For further information please refer Jarke et al [26]

SYSTEM ARCHITECTURE

Zoom+pan interface and the navigation techniques are developed by making use of a number of opensource as well as proprietary APIs.

OpenSceneGraph: is an openGL wrapper API, which consists of a number of libraries and dependencies to other graphics libraries (libtif, libpng, zlib, etc). One of the core OSG library is osgViewer, which supports multi-threaded multiple graphics context usage. One can assign each context to different GPU for multiple screen outputs such as in tiled wall displays, figure-3.3 shows OSG system components.

osgEarth: is a terrain rendering toolkit based on a number of projects such as GDAL, OGR, and OpenSceneGraph. It supports on the fly terrain rendering, requesting map tiles through Open Geospatial Consortium WMS, WCS and TMS protocols.

Openstreetmap: we have referenced osgEarth to openstreetmap tileserver, to download tiles and render terrain tiles on the fly.

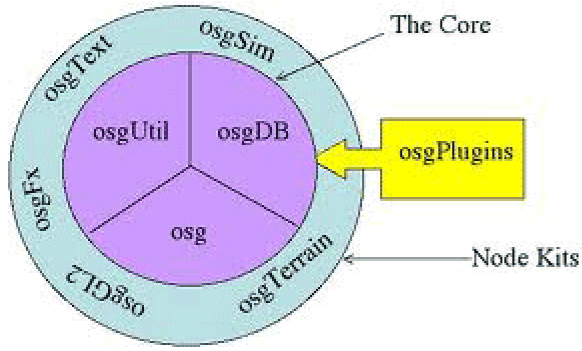

Figure 3.3, OpenSceneGraph System components

The designed zoom+pan interface and navigation techniques can be summarized into the following system components

Filter: For the purpose of smoothing fluctuations and jitter on pose and orientation information we have used 1-€ filter[44].

Gaze Estimator: is a module used to estimate gaze point by using head position and orientation information, and display coordinates in world coordinate system.

Camera Manipulator: is a camera manipulator module used for enforcing different multi-scale navigation characteristics (based on the three navigation techniques discussed in chapter-5). It uses estimated gaze point, covert the gaze point from world coordinate to screen coordinate, and use the transformed point as center point for most of operations used in the zoom+pan interface.

Event handlers: are group of event handlers which are responsible for a number of tasks. some of them are, keyboard and mouse event handlers, camera event handlers, timer event handlers and crosshair event handlers.

Figure-3.4 shows overall system architecture of zoom+pan interface and navigation techniques designed in this thesis project

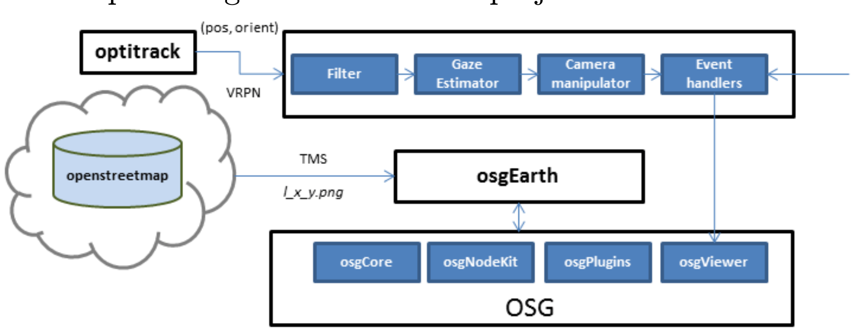

Figure 3.4, System Architecture

CHAPTER 4 - NAVIGATION TECHNIQUES FOR WALL DISPLAY

Information visualization and multi-scale navigation for wall displays has been discussed in earlier works such as Ball et al [12, 13]. In this chapter a brief introduction to physical, virtual and hybrid navigation techniques is presented together with their shortcomings and limitations in multi-scale navigation for large wall displays.

EMBODIED INTERACTION

It has been discussed from earlier works such as [3, 13, 17, 41] that display size improves user's performance in spatial tasks. That is, as the display size increases so does the performance of the user which leads to reduced task completion time and improvement in the overall interaction experience. The main reason behind this is that, larger displays promote the use of physical embodied resources such as *motor memory*, *peripheral vision*, *optical flow*, *focal attention*, *spatial memory* as well as it encourages the use of *physical navigation* [17]. Embodied interaction encourages users to be engaged physically as well as mentally with the system, and better utilize physical embodied resources for solving analytic tasks.

Motor memory is a group of muscle memories and a part of embodied resource, which are genetically pre-wired as well as learned through lifetime.

Peripheral vision is part of human vision system that resides at the edge of field of view. It is very sensitive to movement and less to detail and color compared to central vision. It is often used unconsciously and plays an important role in orientation and navigation. Because of these characteristics, it has been a central point in the design and implementation of peripheral displays, near-eye displays and unobtrusive vision system such as [2].

Optical flow is the continuous stream of input to the eye caused by the movement from the observer or the objects, surfaces and edges that naturally exist in real environment. It has been shown from the research work such as [4] that optical flow plays a vital role in navigation and direction manipulation performance in 3D virtual worlds. Wider field of view and larger displays are also reported as the main factors that improve female navigation speed performance to in 3D navigation [4].

In target detection and identification tasks, *focal attention* plays a major role by identifying salient targets from nearby non-targets and it is very important in identifying target properties in detail [5].

Spatial memory is another part of embodied resource responsible for recording information about one's environment and spatial orientation. Spatial memory allows a person to remember locations and relationships between objects in space, or the ability to recognize and understand spatial relationships. It provides effective aid to spatial awareness, information retrieval and organizations [6]. From the experiment done by [7], immersion, which presumably motivated by large display size, affects spatial memory; a higher level of immersion appears to improve short-term spatial memory.

DISPLAY RESOLUTION

Large high-resolution displays with high number of pixels have the potential to increase the quantity and granularity of displayed information. Display resolution can be defined as the total number of pixels in the display that is available to show the dataset. It depends on two factors; *display size* and *pixel density* of the display.

Display size, sometimes called viewable image size, is a measure of the physical size of the display. It is the amount of screen space available to display the data without obscuration from the case of the display. On the other hand, *pixel density* or pixel-per-inch (PPI) is the resolution in pixels of an image to be printed on the display. It relates the size of the display in inches with the total number of pixels in the horizontal and vertical directions of the display. Ordinary computer cathode ray tube or LCD monitors have pixel density of 67 to 130 PPI.

Display size and pixel density together defines display resolution. Hence, high-resolution displays can be made by increasing either display size or pixel density or a combination of both. While it is possible to increase display resolution by increasing pixel density, as in the case of IBM's Big Bertha [8], the display used for this thesis project is based on increasing the size of the display by using multiple projectors.

Figure-4.1 shows the display used for this thesis project. It is a tiled display consisting of 12 projectors arranged in a 4x3 matrix. Each projector has a resolution of 1920x1080, providing a total resolution of 7680x3240 or approximately 24.8 Megapixels.

Figure-4.1, high-resolution wall display from Human Centered Computing Department of Computer Science, University of Copenhagen, http://www.diku.dk/research/hcc/

NAVIGATION TECHNIQUE

Visualizing data via large wall size display promotes the use of physical navigation, as discussed in research works such as [3, 12, 13, 17, 41]. From Ball et al [3] few participants have been observed to prefer virtual navigation than physical navigation in spatial tasks for hybrid navigation conditions. In this section, we will discuss the basics of the three types of navigation techniques by adopting the notion of space-scale model from [3] and its relationship with virtual and physical navigation from [11].

Physical Navigation

From earlier research works and empirical studies such as [12, 13] we have seen that large displays not only promote the use of embodied resources such as spatial memory, peripheral vision and focal attention, they also encourage the use of *physical navigation*. In return physical navigation proved to be the most important factor in improving performance compared to other factors such as peripheral vision [3].

As opposed to desktop displays, larger high-resolution wall-size displays such as figure-4.1 allow more use of human body's resources to interact physically with display visualization. Physical navigation can be considered as a physical movement that possibly affects user's perception of the viewport data. Moving eyes or head, walking, standing, crouching, and sitting can be considered as forms of physical navigation [13].

Physical navigation has been used in Virtual Environments and data visualization via various types of display technologies such as CAVE, head-mounted displays, projectors and wall-size displays. Each of these technologies has been used for various tasks and each technology has their own affordance and limitation to physical navigation.

In CAVE[1] like environment [14], head and pose tracking is used to promote physical navigation and enable users to wander within the confines of the CAVE room to adjust the 3D view of the virtual environment. Since most CAVE environments are made up of multiple screens that don't fully surround the user, this display technology partially limits free physical navigation.

Compared to CAVE like environment, *Head-mounted Display*s provide a complete 360 FOV of the virtual environment and encourages the use of free physical navigation. However, this display technology totally immerses the user into the virtual environment and obscures the real environment. This results frustration on the user and limits the amount of physical navigation as the user avoids tipping off from or crashing on the real obstacles in the physical environment.

On the other hand we have high-resolution *wall-size displays* where visualization coexists within the real environment. In such environments, display technologies present the data and its interaction into physical space. One prominent example is the work of Greenberg et al [15, 16] where they developed proximity toolkit and a prototype application, proxemics face.

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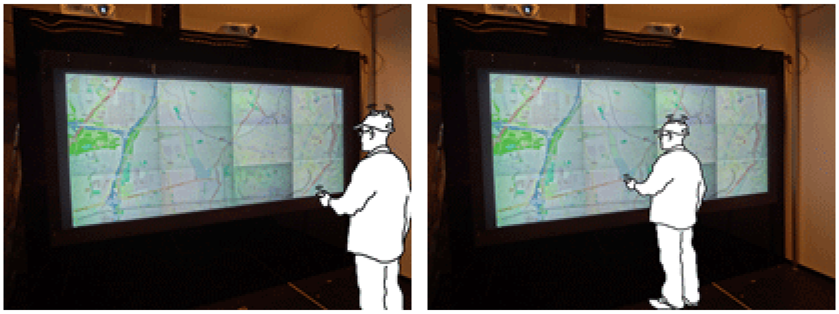
[1] Cave Automatic Virtual Environment (CAVE)
http://en.wikipedia.org/wiki/Cave_automatic_virtual_environment

From the research works such as [13, 15, 16], we can see that large wall-size displays utilizes physical embodied resources and promotes physical navigation through linking the virtual and real environment in a seamless fashion. This intern creates performance improvement in various tasks and better user satisfaction as shown in empirical studies such as [3] and [12].

Figure-4.2, (A) head-up display, (B) CAVE-like environment, (C) tiled display for high-resolution visualization



Figur-4.3, physical navigation through body movement for visualizing Overview (A) and Detail (B), Images taken In Human Centered Computing Department of Computer Science University of Copenhagen http://www.diku.dk/research/hcc/

Virtual Navigation

From the experiments made by Ball & North such as [12], participants tend to utilize their physical embodied resources to visualize the data displayed on the high-resolution wall-size display. They also have been seen to prefer doing physical navigation to visualize the geospatial data in different Level-Of-Detail (LOD). However, few participants have been seen to perform pure *virtual navigation* to visualize the data displayed on the high-resolution wall-size display.

Virtual Navigation is a navigation technique used for changing the view shown on the display by performing *virtual panning* and *zooming* in the information space using external devices such as mice [13].

The amount of physical and virtual navigation has a direct relationship with display size. Large displays promote the use of physical navigation and better utilization of embodied resources. This means that as display size increases, physical navigation increases thereby decreasing the mount of virtual navigation necessary to traverse across the information space. However, for small display devices such as desktop displays, virtual navigation seem to be the main way of navigation since the information space couldn't fit to small displays in its entirety.

For large wall-size displays a number of devices have been developed to perform virtual navigation. Some of them are gyroscopic mouse, infrared mouse that works well in mid-air. As techniques and mid-air pointing devices are getting critical improvements in the past few years, they blur the boundary between physical and virtual navigation, and in fact, creates a *hybrid navigation technique.*

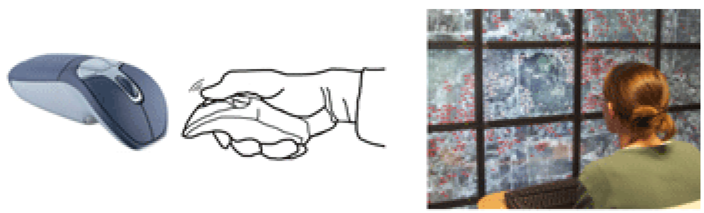


Figure-4.4, (A-B) a gyroscopic mouse, (C) virtual navigation in high-resolution wall-size display

Hybrid Navigation

Large wall-size displays afford the use of physical navigation and minimize the necessary virtual navigation one has to make to move throughout *space-scale*. However, if the data is too large to fit to the large-wall size display, it is necessary to use mid-air pointing devices such as gyration Gyroscopic mousse, so that part of the information space can be spanned by using virtual panning and zooming.

Figure-4.5, Hybrid navigation

SPACE SCALE

In this section we adopt the space-scale model and navigation technique relationship from [13] to better understand the relationship between physical and virtual navigation.

Space Scale Model

In order to define the relationship between navigation techniques using space-scale model, it is important to define certain terms.

Space Scale as defined in Furnas et al [11] has two important parts. *Scale* refers to the magnification or zoom level of the data. *Space* is the total amount of space the data requires to be displayed in its entirety at a given zoom level. *Viewport* is a physical space that the user uses to visualize the information space. Unlike space, which is defined by the zoom level (scale), viewport is a fixed quantity, which depends on the resolution (number of pixels) of the display device. As viewport (display size) increases, we could either perform zoom-in operation to visualize details of the current information space, we could be able to visualize larger area of the information space or we could also do both so that we can see more detail and overview of the information space. This relationship between space, scale and viewport size can be best represented using the space-scale diagram shown in Figure-4.6.

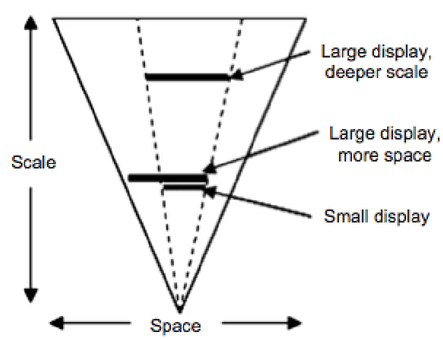


Figure-4.6 space-scale diagram showing how a large display can show more overview and details than a smaller display. Image taken from Ball et al [13]

From Figure-4.6, as the smallest display (the lowest display) size increase, we can hold the zoom level constant and increases the visualization area to see more overview of the information space as shown by the middle display. Or we could hold the visualization area constant but perform a zoom-in operation to see same visualization area with deeper detail as shown in Figure-4.6 by the top display.

Space Scale Navigation

From Ball et al [13] space, scale and viewport has been related by using notion of space-scale diagram. However, we could also see the relationship between physical and virtual navigation if space-scale is augmented by physical navigation as shown in Figure-4.7.

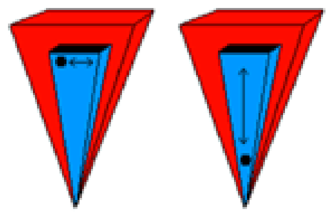


Figure-4.7, Space-scale models augmented by physical navigation. The left model shows how a person (represented by a black dot) performs physical panning. The right model show how a person can physically zoom. Image taken from Ball et al [13]

The red frustum in Figure-4.7 shows, the total area (*space*) the information requires to be displayed and the smaller blue frustum shows the information space that can be seen by the user at that particular zoom level (viewport data). The black dot represents the person performing physical navigation. The left model in Figure-4.7 shows a person performing physical panning by moving sideways parallel to the display. And the right model shows a person performing physical zooming by getting closer or further away from the display.

Physical and virtual panning techniques are similar in that they don't change the virtual zoom level. However, they are different in that physical panning doesn't change the viewport location in space. User can only see what is currently displayed on the screen. Virtual panning can change the view by virtually zooming the viewport in the information space.

Physical and virtual zooming are different in that physical zooming does not change the virtual zoom. As the user get closer or further away from the display, the currently displayed information will be perceived in different level of details. Users naturally use their visual perception to aggregate the details, which can possibly help them to solve pattern-finding tasks. On the other hand, virtual zooming changes the virtual zoom level, which brings more detailed or more overview information to the display.

In summary we can see the relationship between physical and virtual navigation, as well as their difference in panning and zooming technique from the table-4.1 shown below.

Table-4.1, physical and virtual navigation comparisons

	Physical Navigation	**Virtual Navigation**
Pan	• Doesn't change zoom level • Doesn't change physical distance from display • Doesn't change viewport location in space	• Doesn't change zoom level • Performed at constant physical distance from display • Changes viewport location in space
Zoom	• Doesn't change zoom level • Changes physical distance from display • Visual aggregation, visual perception	• Changes zoom level • Performed at constant physical distance • Geometric zooming and/or semantic zooming

Other characteristics of physical and virtual navigation are;

- Physical navigation space is inside virtual navigation space
- As the amount of physical navigation increase the amount of virtual navigation decreases

Most of research works from North and colleagues [3, 12, and 13] have treated physical navigation as physical movement in the interaction space, which is mainly used to perceive visualization in different level-of-detail and aggregate visual encodings into meaningful patterns by observing visualization from many distances, viewing angles and scales [22]. And together with embodied resources such as peripheral vision, physical navigation resulted significant improvement in task performance for spatial tasks such as navigation, search and route tracing tasks. [13]

In this thesis project, we are interested to design navigation techniques which make use of embodied resources, movement and proximity information. One of the motivations of this thesis project is to relate embodied resources, movement and proximity information to multi-scale navigation. That is instead of using Gyration Gyroscopic mouse which drives zoom+pan interface [13], we are making use of user's position and rotation - pose – information to navigate through scale-space. Three navigation techniques has been designed and implemented by using two approaches; device used for virtual navigation and motor-to-display space mapping, which is discussed in the next chapter.

CHAPTER 5 - DESIGNING THE NAVIGATION TECHNIQUES

INTRODUCTION

In chapter 4 virtual, physical and hybrid navigation techniques have been defined and the navigational principles were related with the notion of space scale diagram.

Virtual navigation (virtual zooming and panning) is typically a 3DOF task, the user controls the view's position (x,y) and its scale(s). The main task will be to find varies opportunities for mapping head position and orientation – pose – information and physical movement to the three input channels. In this chapter we present navigation technique design process by following two approaches. We then discuss how the basic navigation tasks (panning and zooming) will be performed using this navigation techniques, and finally adopt state-transition and mode and flow models from Wigdor et al [23] to show the different transition states and modes associated with each navigation techniques.

The first approach used in designing the navigation technique was based on the *resource* required to perform virtual navigation, Table-5.1. Virtual navigation can be performed by utilizing embodied resources (physical movement, head movement, eye movement) or external devices such as mouse as in the experiments made by North et al [12 and 13]. Following this approach, we come up with two navigation techniques. The first one is *proximity based interaction* where the virtual navigation is performed using bodily movement. And the second one is *Gyro based navigation* technique where a Gyration Gyroscopic mouse is used to perform virtual zooming and panning.

Table-5.1 Designing the navigation technique, the first approach

		External device (Gyroscopic mouse)	
		Yes	No
Embodied resources (eye, head, bodily movement)	Yes	X	2. Proximity-based navigation
	No	1. Gyro based navigation	NA

Since one of the objectives of this thesis project is to evaluate performance improvements of bodily based navigation technique compared to Gyro based navigation, navigation technique using both resources was not considered.

The second approach we have followed was based on the mapping of *motor space* (physical space) to the virtual space (*display space*). User's physical location relative to the display can be mapped to the distance of the virtual camera relative to the terrain. In *Absolute mapping* method, the physical distance of the user relative to the display is mapped to the distance of the virtual camera relative to the terrain. This corresponds to absolute mapping in the scale dimension. On the other hand, the one-to-one mapping between user's location parallel to the display and the virtual camera location parallel to the terrain can be considered as absolute mapping in the space dimension.

As defined in Smith et al [25], *Relative mapping* on the other hand refers to the correspondence where motor space, the space where users perform physical actions, and display space, the space that displays visual feedback of an interaction, are not aligned. That is, there is no one-to-one correspondence between physical space and virtual/display space.

Based on the resource required to perform virtual navigation (the first approach) Gyro-based and proximity-based navigation techniques was designed. After applying absolute and/or relative mapping of physical and virtual space, proximity-based navigation technique is divided into three navigation techniques; Absolute navigation, Gaze based navigation and Relative navigation. Table 5.2 shows subdivision of proximity-based interaction techniques.

Table-5.2 Designing the navigation technique, the second approach

<table>
<tr><td colspan="2"></td><td colspan="2">Zooming</td><td colspan="2"></td></tr>
<tr><td colspan="2"></td><td>Absolute</td><td>Relative</td><td colspan="2"></td></tr>
<tr><td rowspan="4">Horizontal Panning</td><td>Absolute</td><td>X</td><td>X</td><td>Absolute</td><td rowspan="4">Vertical Panning</td></tr>
<tr><td>Absolute</td><td>Absolute Navigation</td><td>X</td><td>Relative</td></tr>
<tr><td>Relative</td><td>X</td><td>X</td><td>Absolute</td></tr>
<tr><td>Relative</td><td>Gaze Based Navigation</td><td>Relative Navigation</td><td>Relative</td></tr>
</table>

From all possible mapping combinations there are few combinations that didn't considered for further development. These are represented in Table-5.2 by X.

First, an assumption, which latter supported by the empirical findings discussed in chapter-9, that user's prefer to interact with the display by simply walking instead of crouching, leaning or jumping. This indicates that absolute mapping of user's position for vertical panning cannot be used. Instead, we have computed user's gaze and head pose and used relative mapping by using display boundaries as reference point for multi-directional vertical panning.

Second, if we use relative mapping for zooming, it is a necessary condition that horizontal panning follow the same mapping approach (Relative Navigation). However, it is not necessary condition in the other way round (Gaze based Navigation)

Together with the basic navigation techniques, virtual and physical navigation, these proximity-based navigation techniques (Gaze, Absolute and Relative) can be further analyzed based on the resources required to make use of them. Table 5.3 shows the list of resources required to perform the navigation techniques listed on the left.

Table. 5.3 resources required to perform the five navigation techniques

Navigation Techniques		**Body Movement**	**Head Movement**	**Peripheral Vision**	**Mouse**
Virtual Navigation		No	Yes	Yes	Yes
Physical Navigation		Yes	Yes	Yes	No
(Hybrid) Gyro based navigation		Yes	Yes	Yes	Yes
Proximity based Navigation	*Gaze based Navigation*	Yes	Yes	Yes	No
	Absolute Navigation	Yes	Yes	Yes	No
	Relative Navigation	Yes	Yes	Yes	No

We have two basic virtual navigation operations, zooming and panning. However, it is important to treat panning as horizontal and vertical since we are making use of bodily movement to perform such navigations. Table 5.4 shows, an overview to the techniques required to perform these navigation operations for each of the navigation techniques.

Table-5.4 Virtual navigation operations and navigation techniques

<table>
<tr><th colspan="2">Navigation Techniques</th><th>Zooming</th><th>Horizontal panning</th><th>Vertical panning</th></tr>
<tr><td colspan="2">Virtual Navigation</td><td>Mouse wheel scrolling</td><td>Mouse grabbing</td><td>Mouse grabbing</td></tr>
<tr><td colspan="2">Gyro based navigation</td><td>Mouse wheel scrolling</td><td>Mouse grabbing</td><td>Mouse grabbing</td></tr>
<tr><td rowspan="3">Proximity-based Navigation</td><td>Gaze based Navigation</td><td>Move toward-to/away-from display</td><td>Gazing at horizontal display boundary</td><td>Gazing at vertical display boundary</td></tr>
<tr><td>Absolute Navigation</td><td>Move toward-to/away-from display</td><td>Moving sideways parallel to display</td><td>Gazing at vertical display boundary</td></tr>
<tr><td>Relative Navigation</td><td>Step forward/backward from navigation region</td><td>Step sideways from navigation region</td><td>Gazing at vertical display boundary</td></tr>
</table>

PHYSICAL NAVIGATION

Physical navigation as discussed in chapter 4 and the work of North [3, 12, and 13] is a bodily movement which results in the change of perception of the visualization. Embodied interaction such as crouching, head rotation, and eye and body movement can be used to perform physical navigation.

In designing pure physical navigation technique, we need to make sure that no virtual navigation is possible to visualize the information space. That is, the visualization should be sized to exactly fit the display.

Figure-5.1 shows how users perform physical zooming by walking towards or away from the large wall size display. While making physical zooming, users will perceive the visualization in different detail. That is, they will get the overview while standing further away from display, and detailed information while standing near to the display. On the other hand walking parallel to the display lets users to physically pan the visualization.

Fig. 5.1 Physical zooming and panning

VIRTUAL NAVIGATION

In designing pure virtual navigation technique, it is necessary that the following points should be kept into consideration.

Limited physical navigation

We need to make sure that users only make virtual navigation to traverse across the scale-space. That is we need to restrict the use of physical navigation such as body and head movement.

To prevent users from making *body movement*, participants need to stand and stay in a fixed position in front of the display. A chair can be setup in front of the display and make them sit on that specific place throughout the experiment. However, they will get different viewing angle of the display compared to other navigation techniques such as the three proximity-based navigation conditions, which can only be used by walking around the display room.

Viewport size

Standard desktop displays emphasize foveal vision and provide limited opportunity for physical navigation. This makes them ideal viewport for virtual navigation. However, factors other than physical navigation, such as peripheral vision might have impact on task performance [3], so it is better to use the entire display screen.

Peripheral vision

Large displays have been shown to improve user task performance in high scale visualization tasks [12, 13]. As display size increases, it creates better opportunity to utilize embodied resources such as physical navigation and peripheral vision. From earlier research works and the theory of embodied interaction, physical navigation guided by peripheral vision can produce better navigation strategies and improves user performance. This creates a question as weather the combined effect of physical navigation and peripheral vision is more critical to improved performance than the impact from individual factors.

Since the combined effect of physical navigation and peripheral vision may possibly be more crucial to the performance improvement, it is more interesting to associate peripheral vision to all experiment conditions instead of canceling its effects entirely. For the proximity-based navigation conditions, peripheral vision is already included as natural embodied resource. However, peripheral vision can be included in virtual navigation in either of the two design methods.

- ❖ Method-1: Using wall-sized displays thereby making use of the natural peripheral vision included as part of embodied resource. In this method 19939 by 2883 pixels resolution will be used.
- ❖ Method-2: Using focus+context visualization where the central area displays information in high resolution (focus) while the peripheral area displays information in low resolution (context). The purpose of using the low-resolution context was to mimic the reduced resolution of human peripheral vision, and thereby inhibit any benefit users would gain by cheating and looking outside the focus area (illegal physical navigation).

The first design strategy makes use of natural peripheral vision from the wall-size display. This leads to better visualization while introducing minor physical navigations such as head and gaze movement. The second design strategy would be a focus+context screen, which is similar to Baudische's prototype [20]. In the second method human peripheral vision is approximated which presumably loses certain visual information in the process. Table-5.5

summaries the benefit and drawbacks of the two peripheral design methods disused above. And figure 5.2 shows proper virtual navigation setup.

Table 5.5, peripheral vision design methods

Design Methods	Pros	Cons
Method-1	Natural peripheral vision	Few physical navigation
Method-2	Limited physical movement	Artificial peripheral vision

Figure 5.2, virtual navigation setup

Navigation Types

There are two basic virtual navigation types, zooming and panning.

For zooming, we have designed and implemented two varieties of zooming techniques. *Screen Center zooming (pure zoom)* works by taking the center of the screen as center of zooming. To perform screen centered zooming, control key with mouse left or right key should be pressed together. That is, control key with left mouse button to zoom-in, and control key with right mouse button to zoom-out.

Cursor Centered Zooming ("zoom around") works by taking the cursor position as the center of zooming. User has to position the mouse cursor at any point of the map and use mouse wheels to virtually zoom at that point. That is, mouse wheel up for zooming-in and mouse wheel down for zooming out by taking mouse cursor position as center of zooming. For *panning* users have to drag the mouse to any direction required, and it works in all direction.

HYBRID NAVIGATION

Hybrid navigation is a combination of virtual and physical navigation. That is, it is possible to perform either pure virtual, physical or a combination of both at the same time.

In Gyro based hybrid navigation users are free to walk around in front of the display and make use of their embodied resource to perceive the viewport data in different levels (*physical navigation*). They are also able to visualize parts of the information space, which is not currently displayed in the viewport through virtual panning and zooming (*virtual navigation*) using Gyration Gyroscopic mouse as shown in figure 5.3.

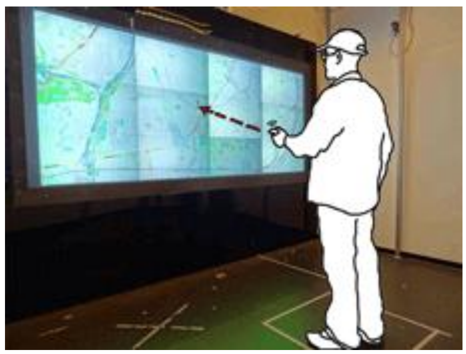


Figure 5.3, Gyro based hybrid navigation setup

In gyro based hybrid navigation users manipulate the viewport data and makes virtual navigation using a Gyration Gyroscopic mouse. This navigation technique is the same as to virtual navigation technique with respect to the basic gesture definitions. However, the state-transition model is different from the virtual navigation and can be described in figure 5.4.

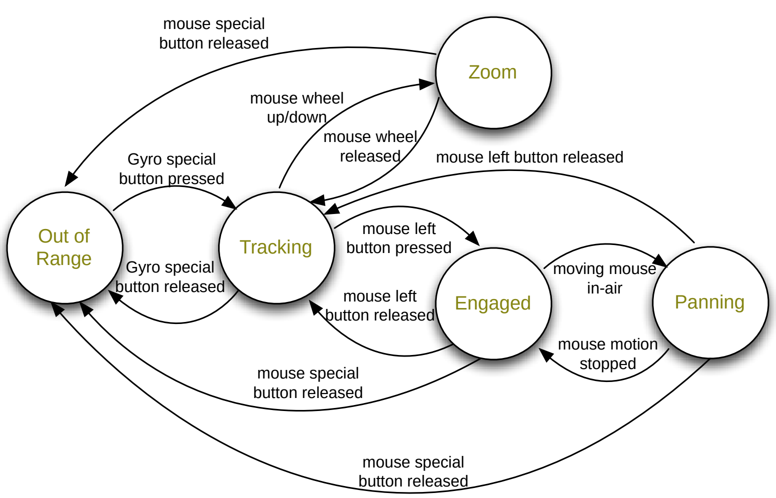


Figure 5.4, State-transition model of a Gyro mouse for Gyro-based Hybrid Navigation

PROXIMITY-BASED NAVIGATION

In proximity-based navigation we are making use of bodily movement and head rotation to manipulate the viewport information. In this section we will present three proximity-based navigation techniques.

Gaze based Navigation

For the Gaze based and the consecutive navigation techniques we are making use of gaze information to provide contextual information for the pan and zoom interface we designed. For these navigation techniques the region/point of interest (POI) is indicated by the users gaze and therefore, we propose to use the user's gaze to indicate the region of interest for zooming. Figure 5.5 shows users gaze (red circle with directional information) on the wall display system running the map pan+zoom interface.

Gaze-based Navigation Gestures and the mode-and-flow Model

In a Gaze based navigation pure zooming is performed by looking at the screen center and make physical movement to or away from display. To perform pure zoom-in, users have to look at viewport center (which will be center of zooming) and approach the display in any direction. For pure zoom-out, users have to look at screen center and walk away from the display in any direction. For "Zoom-around" operation, users can gaze at any arbitrary point on the viewport while walking to or away from display for zoom-in and zoom-out, respectively. The direction users have to walk-in doesn't matter as long as it increase or decrease distance from display for zoom-out and zoom-in, respectively.

Figure 5.5, user's gaze projected on the pan+zoom interface on wall display system

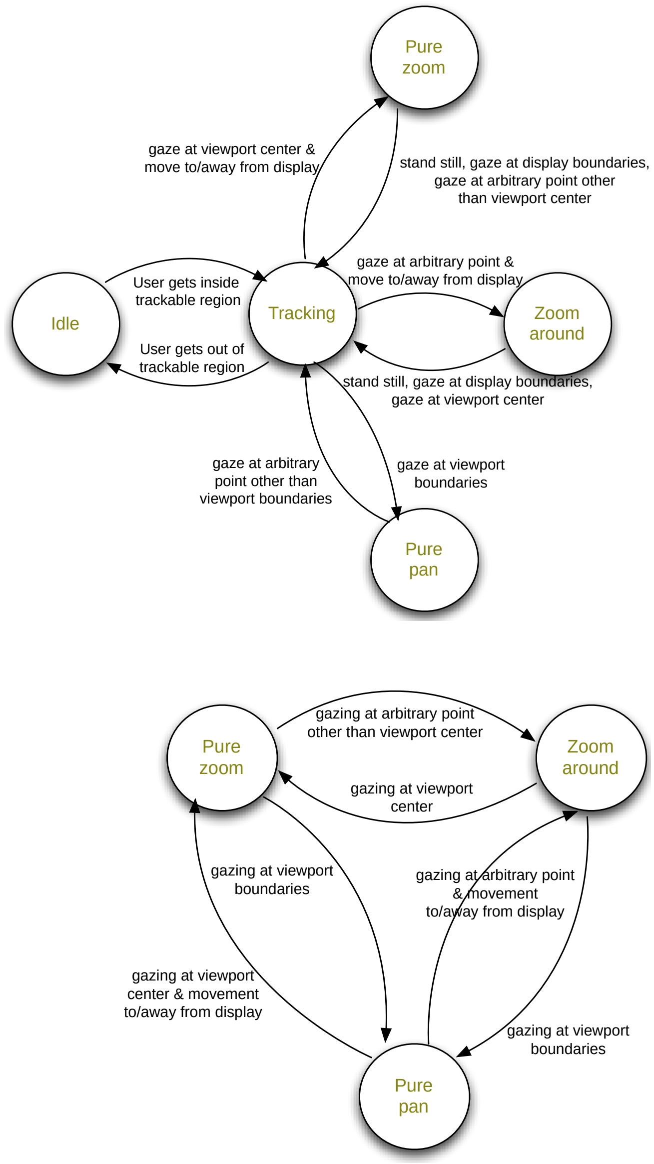


Figure 5.6, mode and flow model for gaze based hybrid navigation

<u>Pure Zoom</u>

In a Gaze based navigation pure zooming is performed by looking at the screen center and make physical movement to or away from display. To perform pure zoom-in, users have to look at screen center (which will be center of zooming) and approach the display in any direction. For pure zoom-out, users have to look at screen center and walk away from the display in any direction. The direction users have to walk-in doesn't matter as long as it increase or decrease distance from display for zoom-out and zoom-in, respectively.

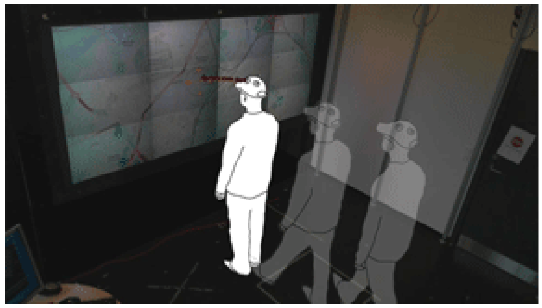
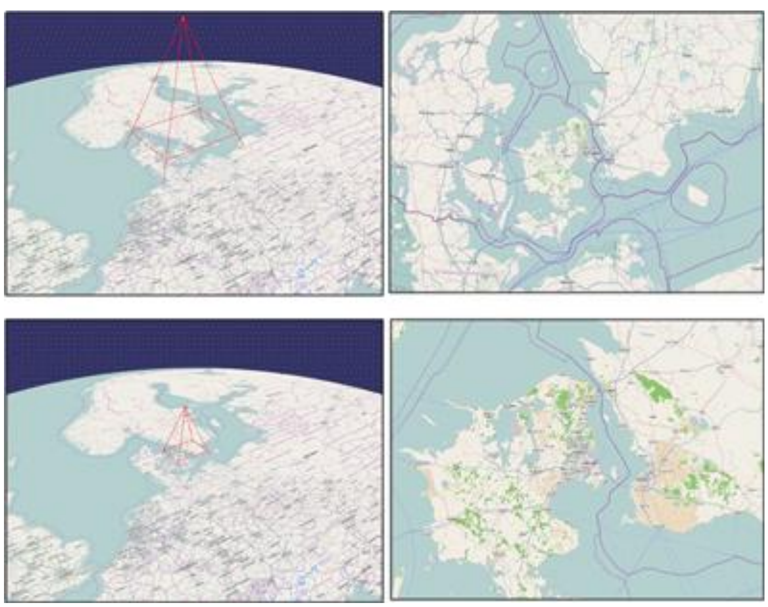


Figure 5.7, screen centered zooming for Gaze based navigation

In gaze-based navigation technique zooming (pure zoom and "zoom around") is designed as *absolute mapping* to physical space (motor space). That is, ther is a one-to-one correspondence between user's location (distance of user from the display) and virtual camera position (distance of virtual camera from the terrain). We have transformed the 2.5 meter long continous *motor space* into 500 discreate zoom levels. These zones are then mapped to discreate zones of the virtual camera on the top of the terrain. As the user moves forward to the display and steps into new motor space zone, the virtual camera steped down into the next virtual space zone, thereby creating the perception of zoom-in. As the user moves away from the display and inters into a new navigatio zone, the virtual camera gets farther from the terrain and enters into a new zone, thereby visualizing an overview of the terrain/map, figure 5.8.



C D

Figure 5.8, virtual camera pos in gaze based navigation, (A&C) third person view of virtual camera's view frustum at zoomed-out and zoomed-in levels, (B&D) zoomed-out and zoomed-in view of the terrain map

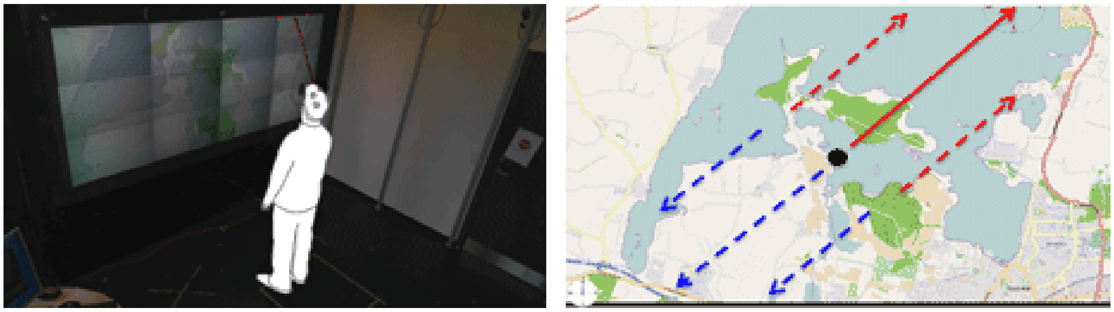


Figure 5.9, (A) panning in gaze based navigation, (B) panning direction (blue lines) and virtual camera trajectory (solid red line)

<u>Pure Pan</u>

In Gaze based navigation technique, panning is done by gazing at display boundaries. Users are required to gaze at the display boundary in a direction where the map should pan. This means that panning works in any direction from the center of the viewport. Figure 5.9 (A) shows a user gazing at display boundary. And Figure 5.9 (B) shows panning direction in blue lines and virtual camera trajectory in red lines.

<u>"Zoom around"</u>

In a Gaze based navigation "zoom around" at a point is performed by looking at any point on the display and make physical movement to or away from display. To perform zoom-in, users have to look at any POI on the viewport (which will be center of zooming) and approach the display in any direction. For pure zoom-out, users have to look at a POI and walk away from the display in any direction. The direction users have to walk-in doesn't matter as long as it increase or decrease distance from display for zoom-out and zoom-in, respectively. Figure 5.10 shows sketch of a user performing "zoom around" gesture at a POI highlighted by the red lines.

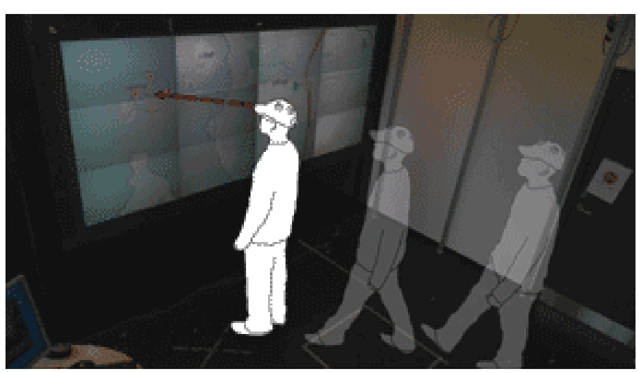


Figure 5.10, a user performing "zoom around" gesture

Absolute Navigation

In section 5.5.1 we have discussed that zooming (pure and "zoom around") works by using absolute mapping. That is, there is a one-to-one correspondence between user's physical locations in the motor space to virtual camera's altitude in the virtual space (information space, display space). Panning on the other hand uses gaze information and doesn't utilize user's location relative to display since user's gaze can be adjusted by standing at any location from the display. Therefore, we have only incorporated one-dimensional (in scale dimension) absolute mapping of motor space into display space while the space dimension uses gaze position relative to the display boundaries (relative mapping). Absolute navigation technique is an attempt to incorporate absolute mapping of motor space into display space in the scale as well as space dimension.

<u>Zooming</u>

Zooming in absolute navigation is the same as to the gaze based navigation technique. We have used absolute mapping of the display space to the virtual space, so that when user walks towards to the display, the distance of the virtual camera to the terrain drops, thereby simulating zoom-in operation. When user walks away from display, the virtual camera gets farther from the terrain resulting an overview of the terrain (zoom-out), refer figure 5.7 and 5.10.

<u>Panning and the animation speed problem in absolute navigation</u>

In designing an interaction technique with absolute mapping in the space dimension, we are mapping the information space to the motor space parallel to the display. In doing this we need to make sure that the animation speed (panning speed) is constant across all zoom levels. However, maintaining constant animation speed while covering the information space in every zoom levels is impossible. To clarify the animation speed problem, we will adopt (u, w) space diagrams from Wijk et al [26] as shown in figure 5.11.

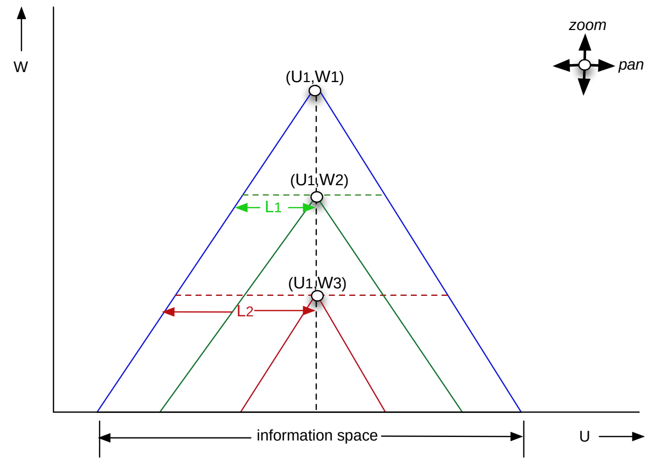


Figure-5.11, u, w space diagram

(u,w) space diagram enables a direct physical interpretation compared to space-scale diagram of Furnas et al [11]. In (u,w) space diagram zooming and panning map to moving a point vertically or horizontally. The axes have the same dimension, both units in world space. The horizontal axis can be considered as a cross-section through the object to be displayed, the point can be interpreted as the virtual camera, floating at a height *w* above the terrain with a field of view of 2arctan(1/2). The path $(U_1, W_1) \longrightarrow (U_1, W_2) \longrightarrow (U_1, W_3)$ is simply the path of a camera flying above the map/terrain in a zoom-in operation.

When mapping the physical panning space (width of the room parallel to the display) to the virtual panning space (U), it is important to keep panning speed constant across every zoom levels.

From the (u, w) space diagram we can see that

$$L_2 = \left(\frac{W_1 - W_3}{W_1 - W_2}\right) * L_1$$

Zooming is achieved by multiplying the current scale by a zoom factor *f*. If we are treating W as zoom index, then we will have $W = \log s$, where s is the scale. Navigating the scale dimension increases or decreases the zoom index by a constant factor $W_f = \log f$. Hence, $L_2 = 2 * L_1$

This shows us that at zoom level W_2, the camera travels $2L_1$ units in time t, with panning speed of $2L_1/t$ units per second. However, at zoom level W_3 the camera is expected to travel on top of the terrain of length $2L_2$ units in time t, with speed of $2L_2/t$, or $2 * 2L_1/t$ units per second. i.e, on zoom level W_3 the camera needs to travel twice as fast as when it was at zoom level W_2 in order to cover the entire information space (refer the 2D view frustum of the red virtual camera in figure 5.11).

To work around the *panning speed problem* in absolute navigation, we have made a predefined panning area (part B-C from figure 5.12) for each zoom levels so that the panning speed will be constant across all zoom levels; hence providing the impression of uniform and constant motion of the projected image on the screen, refer figure 5.12.

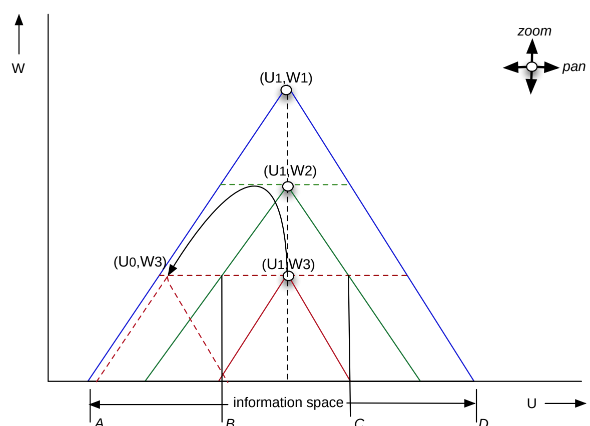


Figure 5.12, A workaround to the animation speed problem, the black curve shows the optimal path for navigation of the information space outside the predefined area

In order to visualize part of the information space outside the pre-defined panning area (a-b and c-d in figure 5.12), the user has to zoom out to certain level where the target can be seen, and perform zoom-in at the target ("zoom around" at target point), as shown by the black curve $(U_1, W_3) \longrightarrow (U_0, W_3)$ in figure 5.12.

Absolute Navigation Gestures and the mode-and-flow Model

Figure 5.13 shows the mode-and-flow model of absolute navigation refereeing to the four gestures used to perform navigational operations.

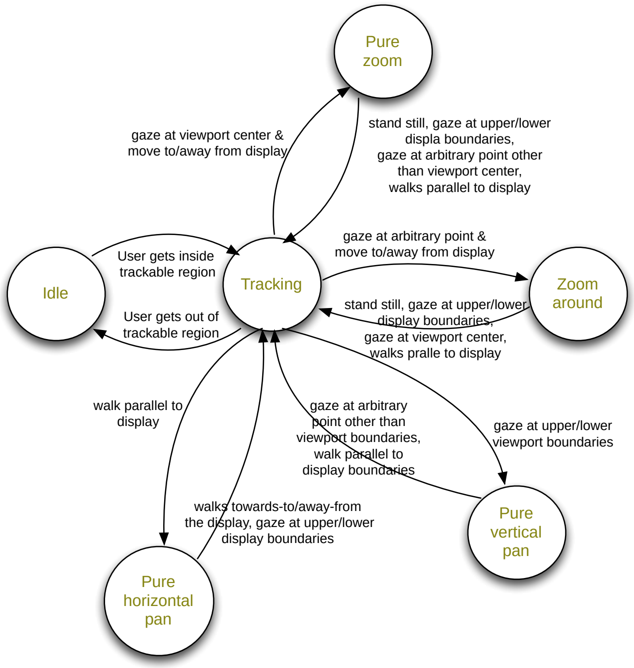


Figure 5.13, mod-and-flow model of absolute navigation gesture language

Relative Navigation

As defined in Smith et al [25], *Relative mapping* refers to the correspondence where *motor space*, the space where users perform physical actions, and display space, the space that displays visual feedback of an interaction, are not aligned. That is, there is no one-to-one correspondence between physical space and virtual/display space.

In our relative navigation technique, we defined a *hotzone*, a rectangular area in front of the display marked on the floor with a white duct tape as shown in figure 5.14. This hotzone area is part of the motor space, which will be used as a frame of reference for virtual navigation operations (virtual zooming and panning).

To perform zooming user has to step out of the hotzone and move towards to the display. When the required zoom level reaches, user should step back to the hotzone to stop further zooming. To zoom out to a lower level view, overview, user should step out of the hotzone in the direction perpendicular and further away from the display, and again user has to step back to the hotzone to stop further zoom-out.

To perform panning user has to step out of the hotzone and move sideways parallel to the display. When the required view is set in the viewport, user should step back to the hotzone to stop further panning. Panning works in such a way that when user moves out of the hotzone in a right direction, the map pans in left direction and the other way around for the left panning. Figure 5.15 shows the display room floor divided into navigation spaces.

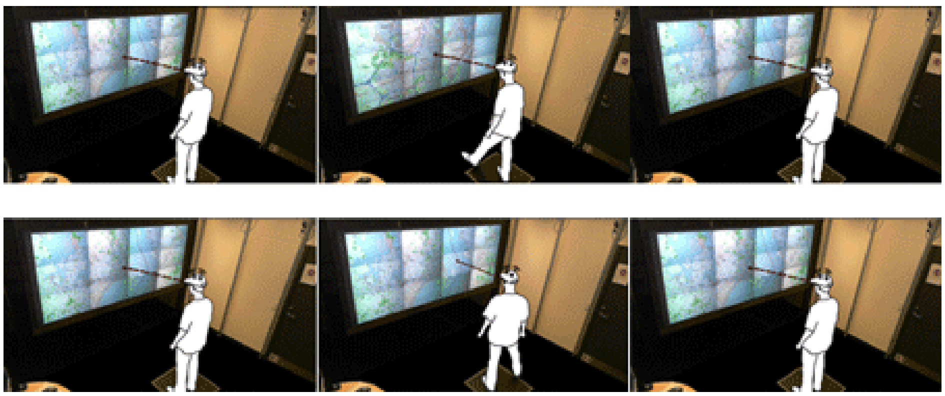


Figure.-5.14 relative navigation gestures

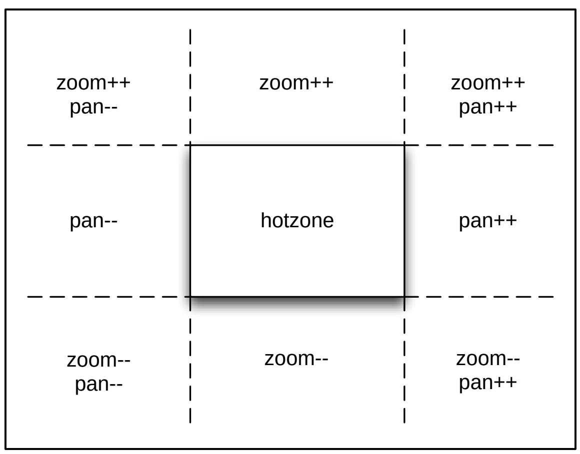


Figure.-5.15 floor of the display room divided into navigation space

Other than the four basic navigations (zoom-in, zoom-out, pan-left and pan-right), we have also made four navigation types out of the four possible combinations from the basic navigations. These navigation types, (zoom-in, pan-left), (zoom-in, pan-right), (zoom-out, pan-left), (zoom-out, pan-right), are then mapped to the navigation space in a way easier to understood by the users, as shown in figure 5.15.

CHAPTER 6 - USER STUDY AND NAVIGATION TECHNIQUE IMPROVEMENTS

INTRODUCTION

In chapter 5, we have used two approaches to design three hybrid navigation techniques including the baseline gyro based condition. We have discussed how the basic navigation tasks can be performed using these navigation techniques, and finally adopted state-transition and mode-and-follow models to show the different transition states and modes associated with each navigation techniques.

In this chapter we will discuss the user study we made prior to the actual empirical study. We will start by discussing the different tasks involved in the experiment. We will then present qualitative analysis of the comments we got from the experiment. And finally we will present the design decisions and major modifications we made for each navigation techniques.

OBJECTIVE OF THE USER STUDY

As discussed in Greenberg et al [32], usability evaluations are main part of HCI and are a critical and necessary component in the interaction design process. Hence, we have made user study with sole purpose of acquiring qualitative data about our navigation techniques design decisions.

TASK DESCRIPTION

Two spatial tasks are designed for the user study. Participants were given a Gyration Gyroscopic mouse to manipulate task targets while navigation the map in either of navigation techniques discussed in the previous chapter. Since the objective of this user study is to gather qualitative comments about the navigation techniques, time and accuracy and other factors haven't been registered.

Navigation

In navigation task, participants are given a target with spatial location around Copenhagen area. Targets are initially displayed as red markers showing that it cannot be manipulated. When the appropriate zoom level reaches, the target turns into green informing that tasks can be completed by clicking on the bounding box of the target.

Search

In Search task, participants were given a textual landmark description of a natural feature from the map such as lake, park, zoo, etc. The task here is to find and locate targets and call out to the experimenter.

Route Tracing

In route tracing task, 10 markers are displayed on top of 10 train/metro stations in Copenhagen area, and train route is displayed by connecting the markers using orthographic line geometry. The markers are initially located few pixels away from the actual train station location. The task here is to drag and put the markers onto the nearest train/metro station.

IMPROVEMENTS OF NAVIGATIN TECHNIQUES

In this section we will discuss improvements and design decisions made after the analysis of participant's comments. We start by discussing four design changes as part of general design decision, followed by one for gaze based and two design changes for absolute navigation.

General Design Decisions

I. <u>Introducing *Resizable Dragged Cursor*</u>

In order to complete tasks in the pilot study, a gyroscopic mouse is used to point and manipulate the targets according to task specifics in the study. This means that the participants should be able to easily locate the mouse cursor as it hugely affects task completion time. During the user study we have observed that the participants had hard time locating the cursor as it is usually farther away from the gaze point. To solve this problem, we referred the MAGIC approach from Zhai et al [27].

In MAGIC (Manual and Gaze Input Cascaded), the cursor is centered in gaze tracking position on or nearby the true target, where the true target can be anywhere within the gaze circle with 95% probability.. Anders et al [18], have proposed a variant of MAGIC approach called *Dragged Cursor*. It is slightly different from MAGIC in that the cursor is constantly presented within a predefined circle around "Estimated Point of Focus, EPOF", the *focus circle.*

In the Dragged Cursor method, the technique attempts to achieve two things. One, the cursor will always be close to where it is needed, as it will never be further away than the border of the focus circle. Two, the cursor location will be predicable, since it will always either be visible in the area of focus, or be approaching from its previous position. Within the focus circle, the mouse cursor can be dragged and repositioned to any point within the focus circle, thereby allowing users to easily acquire the targets and complete the task in less time.

Figure 6.1 shows the functional flow of dragged cursor method from Anders et al [18]. The bigger dashed circle is the focus circle and contains the gaze point, which is shown as a crossed smaller circle. The focus circle defines the area where the cursor can freely move around. The focus circle (dashed circle) moves as the gaze point moves around the display. If the cursor breaches the focus circle (either by mouse movement or gaze movement), the cursor will be dragged in the gaze direction and relocated to the boundary of the focus circle (technically 25 pixels from the crossing boundary inside the circle).

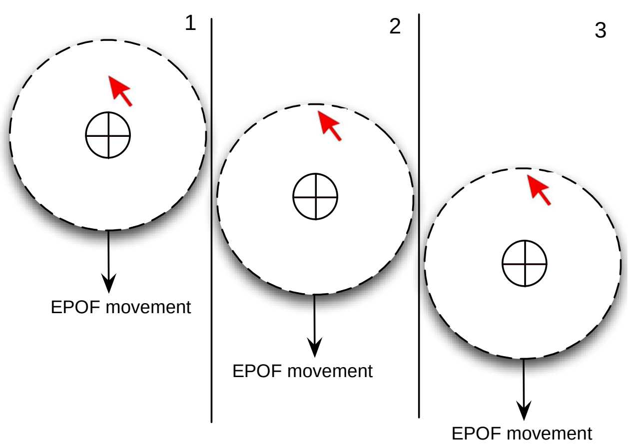


Figure. 6.1 The Dragged cursor methods. From part 1-3, EPOF moves downward without any mouse movement. Between 2 and 3, cursor breaches the circle and is dragged along the edge of the circle, image taken from Ander's et al [18]

In large wall-size display settings, users can be close to the display where their field of view is too narrow, or further away from the display where they can be able to see all part of the display at once. This means that gaze point is too dependent on the proximity of user from display, and we require the cursor to be at nearby position to gaze point. This motivates us to the development of a *resizable dragged cursor.*

In resizable dragged cursor method, the focus circle dynamically resizes to approximate the user's field of view. When users gets near to the display the focus circle becomes smaller and its size will dynamically increases as users gets farther away from the display. We have applied absolute mapping of physical distance to size of focus circle, resulting about 500 focus circle levels.

Figure 6.2 shows relationship between user's display proximity to size of the focus circle. Starting from 2.3 meters to the farthest location from the display (2.5meters), the focus circle has the same size (1600 pixels in radius). And, from the closest point to a location 0.3 meters from the display, the focus circle is sized to 600 pixels. In between these regions, the focus circle dynamically resizes itself with about 3.5 pixels in every level.

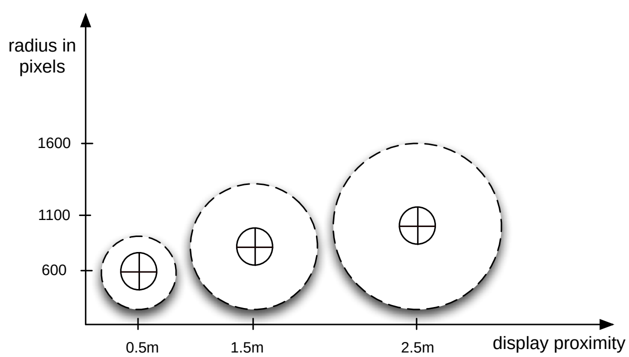


Figure. 6.2 The Resizable Dragged cursor methods. As user's display proximity varies, the focus circle will automatically resize to approximate user's focal area

<u>The two *vertical panning* problems</u>

In order to calculate Point of Interest (POI) or gaze point, we have only make use of head position and orientation. Users are required to wear a hat, which has four markers. The rigid body which is made out of this markers is the tractable we use to estimate head position and orientation. Using just this single trackable, we are able to approximate the user's point of focus and project this gaze on to the screen as a movement feedback for the users. (Provides awareness for self-orientation and position, and will make the system more predicable since the gaze point is used as center of most operations such as "zoom-around")

This single head trackable however, is physically located few centimeters atop of user's eyes. That is, the projected gaze will be deviated from the actual gaze location by few centimeters high and can potentially create problems.

From the user study participants made a comment that panning in the vertical direction doesn't function well. We have also observed that when they try to look at the targets nearby the upper display boundary, the gaze point breaches the upper boundary thereby triggering *unintended panning problem* in that direction (figure 6.3). The same problem but in slightly different way happened when participants try to pan in downward direction. In performing downward panning, they tried look at the lower boundary at the same time acquiring contextual information of the information space via their focal and peripheral vision. However, the estimated gaze point is atop of the actual focus point by few centimeters, which makes them to look further down beyond the lower display boundary. Because of this, their vision has been partially blocked, thereby creating *blocked vision problem*.

To solve the two panning problems, we have two options. One, we can optimize the accuracy of gaze estimation, not only by using head pos but also by including eye information. Second, we can geometrically approximate the EPOF we found by using head pos information to the actual gaze.

The first approach is the optimal solution to gaze estimation and it has been discussed in several research works such as [28, 29, 30]. However, developing hybrid gaze estimation assumed to take quite some time and is out of the scope of this thesis project. Therefore, we have followed the second approach and make an estimation to the actual gaze from the estimated gaze point we got from head pose using simple geometric technique (using h as 50 pixels), as shown in figure 6.3 and 6.4.

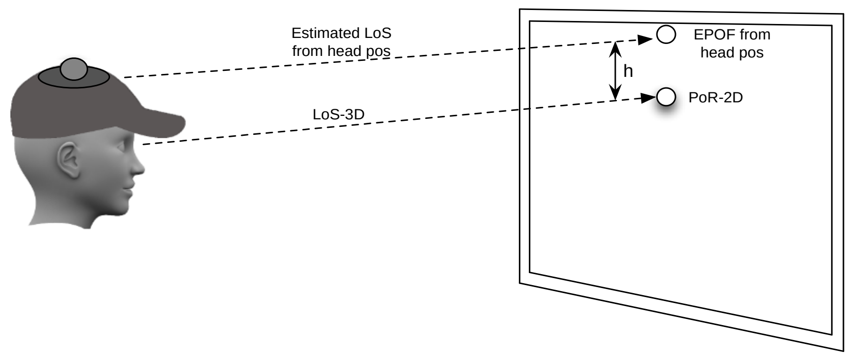


Figure. 6.3 The unintended panning problem. As user's try to focus on targets nearby upper display boundary, the EPOF from head pos breaches the upper boundary thereby triggering unintended panning

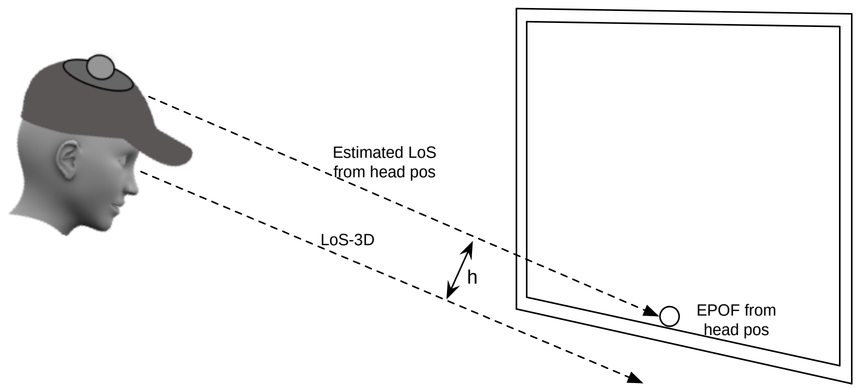


Figure. 6.4 The blocked vision problem. As users try to pan in downward, they have to gaze beyond the lower display boundary thereby creating blocked visions

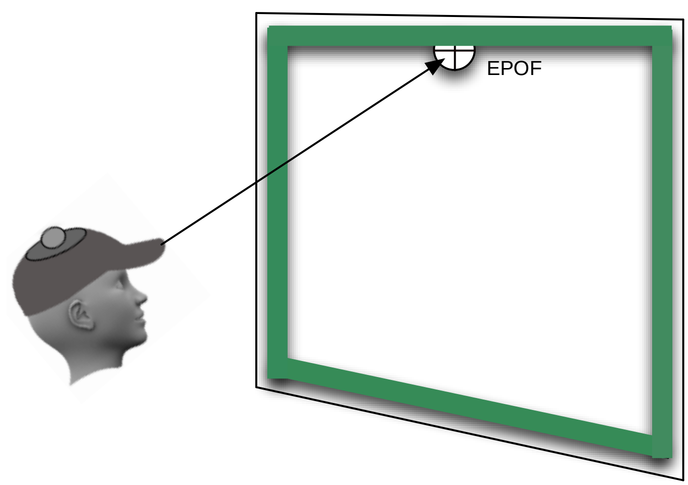


Figure. 6.5 Visual feedback for gaze based panning approach. When the EPOF breaches boundary of the display, a thin rectangle displays informing that after a second, panning will happen in the direction of the EPOF through this boundary.

II. Gaze Based Panning and Visual Feedback

As part of the unintended panning problem, we have thought about introducing an additional solution as a feedback mechanism. The main premise is that if users know prior to when panning operation happens, they have the option to cancel the event thereby preventing the unintended panning problem. The feedback mechanism works as follows; When the gaze point breaches boundary of the display, a thin rectangle displays informing that after few seconds (e.g. 2s), panning will be performed in the direction of the gaze point through this boundary.

III. Screen Centered Vs. User Centered Panning

In all the three proximity based navigation techniques panning in the vertical direction has been designed by using relative mapping. That is, the user gaze at boundary of the display and the virtual camera will fly in the direction parallel to the vector from the screen center to the gaze point. This results the map to pan in the direction opposite to this vector brining the relevant information space to the center of the screen; hence the name *screen centered panning.*

Screen centered panning approach works best in the conditions where the user usually stands in front of the center of the screen, such as in the relative navigation condition. However, for the other navigation techniques it might not be the optimal approach to follow since users can be anywhere in the display room while performing panning. This assumption has been backed up by the comments we got from the first pilot study. Participants commented that the point of interest (POI) keep shifting to the center of the screen while they are standing far from the center, forcing them to move to the center of the screen. This motivates us to re-design the panning technique.

The main objective of our solution to the vertical panning problem in screen centered panning is to find smooth and efficient trajectory for the virtual camera. Smoothness introduces constraints that the path should not include sudden steps or abrupt changes in direction. Efficiency indicates that the path length should be minimal and passes through POIs, thereby bringing focus points to the user location, not the other way around as in the case of screen centered panning. We called this method *user centered panning.*

Figure 6.6 shows screen centered and user centered panning methods. The two black lines show vectors of head projections onto the display and estimated point of focus. Blue and Red dashed lines show virtual camera trajectory for screen centered and user centered panning, respectively. The Blue and Red solid lines show panning direction for screen centered and user centered panning, respectively.

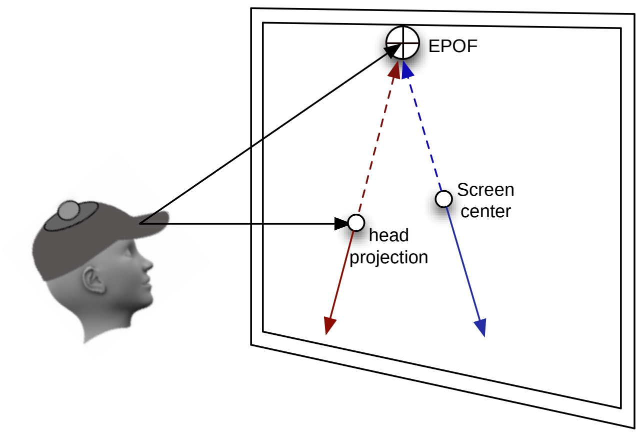


Figure. 6.6 Screen centered and User centered panning. The two black lines show vectors of head project onto the display and estimated point of focus. Blue and Red dashed lines show virtual camera trajectory for screen centered and user centered panning. Blue and Red solid lines show panning direction for screen centered and user centered panning, respectively.

Gaze based Navigation

I. Attention Aware Display

In Gaze based hybrid navigation technique, user's gaze point is used to perform panning operation. When user's gaze point breaches the boundary of the display, it triggers movement of the virtual camera, thereby creating a panning of the map in the direction opposite to the gaze point vector. When gaze point breaches display boundary, panning event will be triggered and the gaze point will remain fixed at the display location where the breaching happened thereby creating continuous panning in the direction opposite to gaze vector. Panning stops *only* when user shifts gaze point from the boundary to other part of the display.

We have observed from the user study that when users gaze away from the display for example, when they are chatting with other person in the room, or lost their focus from the display, the map performs unintended panning. This is from the fact that the display doesn't react to people's attention. This is a motivation to the development of *attention aware display* (as discussed in Greenberg et al [31]) for gaze based hybrid navigation.

One approach to design attention aware display is by defining attention area from user's Field Of View (FOV). If user's gaze point is within this area, the system interprets that the user is actively using the screen thereby exposing all operations such as gaze based panning. If user's gaze point deviates the boundary of this attention area and stayed out for more than some predefined time, then display interprets this orientation as lack of attention and automatically enters into deactivated mode and doesn't respond to any user's gestures or proxemics change. When user turns to look back at the display (within attention area), the system will resume.

Relative Navigation

I. Restructuring the Navigation Space

In relative navigation technique, we have divided floor of the display room into eight regions (navigation space) and mapped it into the four basic navigation operations (zoom-in, zoom-out, pan-left and pan-right) and to their possible combinations, auxiliary navigation operations (zoom-in, pan-left), (zoom-in, pan-right), (zoom-out, pan-left), (zoom-out, pan-right).

We have observed from the user study that three participants complained about relative navigation operation. One of the participants said "I have to remember all eight regions and makes me to think where to step-in, which again makes me to loose attention on the displayed information". We have also observed that some of the participants making unintended navigational operation. For example, one of the participants tried to zoom in (zoom++) but keeps getting into (zoom++, pan--) region. Participants have also been observed that they frequently choose to perform the four basic navigation operations (specially zoom++ and zoom--) than the auxiliary ones.

If we are looking at navigation space division, the hotzone is small part of the floor with area 50cm^2 compared to the area of the room 3x2.8 m^2. From the current space division this means that large area of the floor space is allocated to the four auxiliary navigation operations compared to the basic navigation operations, figure 6.7-a.

In the new navigation space division, we have the same eight navigation zones. However, we have restructured it such a way that maximizes floor area to the four basic navigation operations as shown in figure 6.7-b.

In the new navigation space division, figure 6.7-b, we have chosen increasing motor space for zooming operation than panning. This is because zoom operations is not “pure zoom” instead it is implemented as “zoom around”. Which means by just doing “zoom around” we can zoom as well as pan at the same time. Therefore, more space should be allocated to this navigation operation. From figure 6.7-b we can see that more space is allocated for zoom++ and zoo-- which presumably solves the confusion problem we observed in the user study.

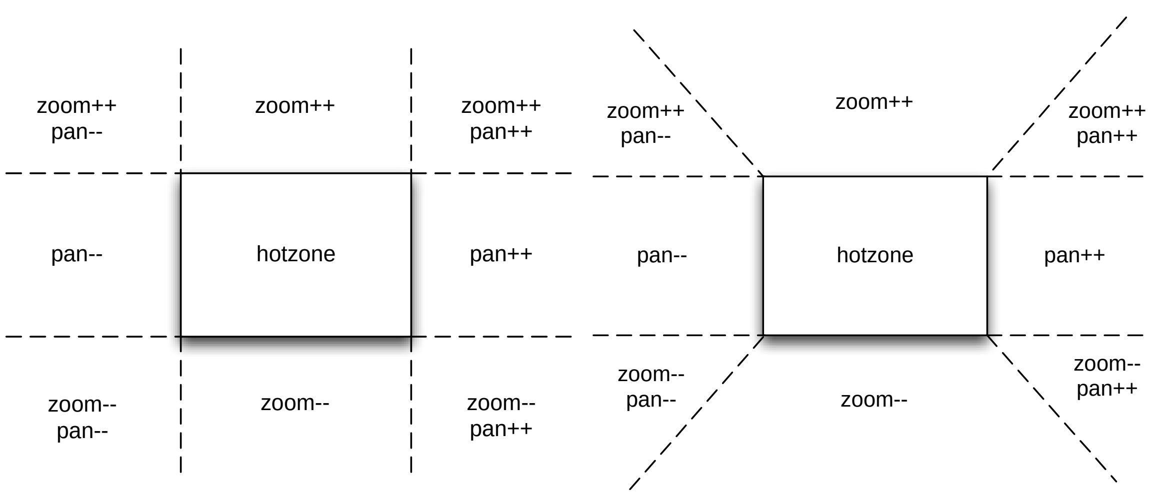


Figure. 6.7 Restructuring the navigation space. (a) the original navigation space division, (b) the new navigation space division, we can see that more space is allocated for zoom++ and zoom--

CHAPTER 7 - EXPERIMENT - DESIGN

INTRODUCTION

In chapter 5 we followed two approaches for designing four navigation techniques, (1) resources required to perform virtual navigation, and (2) mapping of motor space to virtual space. Following the design process, we made a follow-up user study prior to conducting the actual experiment. This results us to a deeper level analysis of the design we made in chapter-5. We then re-designed the interfaces and techniques in chapter-6 based on the analysis of qualitative comments we received from the user study. Following the user study and the experience developed throughout the designing process, we then created spatial tasks and perform pilot study prior to the actual experiment.

In this chapter the empirical study design of this thesis project has been discussed. The main themes of this experiment is to further study proximity based navigation techniques and evaluate them against the hybrid/gyro based condition in terms of performance (task completion time) and user satisfaction using four spatial tasks. Section 8.2 presents the six hypotheses of this experiment. Section 8.3 and 8.4 discusses about experiment design and dependent variables of this experiment, respectively. In section 8.5, the four navigation techniques are presented. And finally from 8.6-8.9, Information visualization and tasks, participants, apparatus and the procedure followed in conducting this experiment is discussed.

HYPOTHESES

Based on the discussion in previous chapters and earlier research works, we have identified six hypotheses.

Hypothesis – 1: Since Head movement is required in Gyro/Hybrid navigation condition; we will not get significant increase in the amount of head rotation for proximity-based navigation techniques.

Hypothesis – 2: Since Head movement is required in Gyro/Hybrid navigation condition; subjects will not experience significant increase in the amount of neck fatigue in using proximity based navigation techniques.

Hypothesis – 3: Since Gyroscopic mouse drives multi-scale navigation in Gyro/Hybrid navigation technique; we will get significant increase in the amount of bodily movement for proximity based navigation techniques. Hence, participants will experience significant reduction in the amount of hand fatigue.

Hypothesis – 4: Since there is significant amount of bodily movement for proximity based navigation techniques, subjects will be engaged in performing tasks, their spatial and motor memory will be utilized. Therefore, proximity based navigation technique will have less task completion time.

Hypothesis –5: Since target acquisition and multi-scale navigation are decoupled in proximity based navigation techniques, participants will have a chance to make the two actions simultaneously. Therefore, the proposed navigation techniques will primarily outperform Gyro/hybrid based navigation for tasks that benefit from this characteristic; one prominent example is train route tracing task.

Hypothesis –6: Because of a complete one to one correspondence in motor-to-display space mapping, absolute navigation will have less mental effort to complete the tasks compared to the other proximity based navigation techniques.

EXPERIMENT DESIGN

We have conducted a controlled experiment following within-group design approach using 10 participants as a subject. There are two independent variables: (1) Navigation techniques (Hybrid/Gyro based, Gaze based, Relative and Absolute Navigation) and (2) Task types (Navigation, Route tracing, Search-I and Search-II). Therefore, each participant completed a total of 4X4 (navigation technique x task types) = 16 task types in the experiment.

We are comparing the performances of the same 10 participants under different conditions. Therefore, the impact of individual difference is effectively isolated and the difference arisen from navigation techniques and task types can easily be observed from few participants we have in the experiment. All participants are exposed to the four navigation techniques to complete four tasks. The order of navigation technique is important. Therefore, we have used 4x4 Latin squares. This makes detection of significant results for navigation technique. Within each block tasks are selected randomly using another 4x4 Latin square. Moreover, participants get adequate training prior to the experiment. Hence, the learning effect is well controlled. Please refer Appendix-C for experiment condition, task order and task dataset randomization procedure used in this experiment.

To complete the experiment participants are required to complete 4x4xN tasks (4 navigation techniques, 4 tasks and N repetitions ranging from 3-10 depending on task types).

DEPENDENT VARIABLES

In this experiment multiple dependent variables have been monitored. Amount of physical and gaze movement, Gaze-display boundary collisions, amount of virtual navigation and task performance during the experiment. Of all these variables, we have chosen performance and user satisfaction as the main dependent variables for this study.

Performance: performance is considered as the time taken to complete a single task. It is measured in milliseconds. It is measured from the time subjects start working on the tasks using any of the navigation techniques until they completed the task. Time tracking is automatic with minimal input from the experimenter, (only two key presses before and after task sequence begins). For example for the 10 targets in navigation task, experimenter will press only a single key to start the timer for the first target. For the remaining targets, the system will automatically track performance time by enforcing 100% task completion accuracy.

User satisfaction: user satisfaction is measured by proving Likert scale questionnaires, which mainly focuses on fatigue, and mental effort required to complete tasks using the technique in questions.

Amount of physical and gaze movement: We have independently tracked amount of physical movement and gaze movement during the experiment. For gaze movement, we have tracked participants head position and rotation to approximate gaze location, and applied 1€ filter from [44] to smooth out jitters. For physical movement we have registered participant's 3D location every second for latter analysis of true physical movement.

Amount of virtual navigation: Virtual navigation has been performed using different techniques for the four conditions; gyro mouse for hybrid/gyro based navigation, and different bodily movement for proximity based navigation techniques. It is very important that we adopt a strategy of measuring virtual navigation that will work for all conditions. Hence, we have tracked position of virtual camera and calculate the displacement of its trajectory once in every 0.04 seconds (that is in every frame since the simulation system has approximately 25 FPS).

Gaze-display boundary collision: we have also tracked the number and location where the estimated gaze point touches the display boundary. This action can be unintended or completely intentional as in the case of gaze based panning and vertical panning for all proximity based navigation techniques.

CONTROLED FACTORS

There are few independent variables that potentially affects the outcome of this study. The following are nuisance factors that are controlled across all experiment conditions.

Target Acquisition Technique: for all experiment conditions, we have used gyroscopic mouse with resizable dragged cursor as pointing and target acquisition technique. In this way, hidden effects caused by target acquisition method will be eliminated.

Panning range: for hybrid/gyro condition, participants will use gyroscopic mouse and resizable dragged cursor method for virtual navigation. In this method, one of the requirements is that the cursor can't breach focus circle's boundary. This is a huge limitation to virtual panning using gyro mouse since panning range is limited by the diameter of the focus circle. For this reason, we have re-designed the method in such a way that, cursor can breaches the focus circle only in panning mode (mouse grabbing).

Animation time: we have used constant animation speed for all navigation techniques in zooming operation. When animation time gets lower than certain value, the animation looks slower and unresponsive. And when it sets to higher value, the animation doesn't look smooth. Hence, we have implemented a simple GUI and made a user study of 3 participants (including the author of this thesis) to find out good animation speed for zooming operation. We have found out that the zooming operation requires on average 0.2 seconds in wall clock time. That is, the virtual camera takes 0.2 seconds to travel from current zoom level to the next.

Figure 7.1, *a simple GUI to find out nice animation speed for zooming operation.*

We have also tried to control the associated **learning effect** in using within-group design. To minimize the negative impact of learning effect, we have allocated 5 minutes long training period for each navigation techniques covering a single example task from all task types. We have also made the tasks with minimal cognitive load. Sufficient time for training, random assignment of conditions and tasks and very limited cognitive load of tasks (based on target's color, which requires basic motor skills for navigation and low mental effort) will effectively control the learning effect.

For controlling the negative impact of **fatigue** during the experiment, we have *forced* the participants to take 5 minutes break in-between experiment conditions (navigation techniques). During this period they sit at a chair and fill out the Likert scale questionnaire which is prepared to assess their satisfaction in using the navigation technique.

GYRO BASED HYBRID NAVIGAITON TECHNIQUE

In Gyro based hybrid navigation users are free to walk around in front of the display and make use of their embodied resource to perceive the viewport data in different levels (*physical navigation*). They are also able to visualize parts of the information space, which is not currently displayed in the viewport through virtual panning and zooming (*virtual navigation*) by using Gyration Gyroscopic mouse.

PROXIMITY BASED NAVIGATION TECHNIQUES

We have followed two approaches to design and implement navigation techniques for virtual navigation using bodily movement; resources required to perform virtual navigation, and mapping of motor space to virtual space.

Gaze Based Navigation Technique

For gaze based and the rest of proximity based navigation techniques we are making use of gaze information to provide contextual information for the pan and zoom interface implemented. For these navigation techniques the region/point of interest is represented by the user's gaze, and is used to indicate the region of interest for zooming. Figure 5.6 shows users gaze (red circle with directional information) on the wall display system running the map pan+zoom interface. We have collected qualitative data from the user study and re-designed the method which presumably improves performance and user satisfaction.

Absolute Navigation Technique

In absolute navigation technique, the motor space is mapped to display space in a one-to-one correspondence fashion for both directions; parallel and perpendicular to display screen. We have discussed in section 5.4.2 that absolute navigation is more natural and the interaction is presumably looks more predictable. However, there is additional movement in the motor space required as a workaround to the animation speed problem and might affect task completion time.

Relative Navigation Technique

In relative navigation technique, we defined a hotzone, a rectangular area in front of the display marked on the floor with a white duct tape as shown in figure 5.15. This hotzone area is part of the motor space, which will be used as a frame of reference for virtual navigation operations (virtual zooming and panning). To perform navigation operations, user has to step few inches out of the hot zone, and step back in to stop the incremental navigation, figure 5.14 - 5.15. After the user study, we re-designed relative navigation technique, which presumably results significant improvement from the prior design.

INFORMATION VISUALIZATION AND TASKS

The visualization is a semantic zoom+pan interface developed using OSG, an openGL wrapper API. The map is a small section of the entire OpenStreetMap [39] dataset around Copenhagen area. We have used osgEarth project [40] for handling spherical Mercator projection and on-the-fly terrain rendering.

For this empirical study, we have made four spatial tasks, navigation, search-1, search-2 and route tracing tasks. Navigation and search tasks consist of 10 and 5 trials and for each trails, targets are located randomly around Copenhagen area, on top of the terrain rendered from OpenStreetMap [39]. For route tracing task, there are 4 train route lines where each of them consists of 10 targets located on top of train/metro stations.

All tasks are displayed as the most overview position of the map. And the targets are displayed with right-sized markers to make sure that participants can easily see the targets without any effort before proceeding to the task. This is important in that we need to be sure to measure the performance time for using the navigation technique not participants perception. The task will be completed when they make necessary zoom level and clicked on the target.

Search-1 task involves finding one of the four targets that turns from blue to green when certain zoom level reached. We have chosen color-based targets instead of textual/numeric values since it doesn't require too much mental effort to accomplish the task unlike numeric valued targets in North's empirical study [13]. We have made four possible solutions per search task, with 0.4 probability of finding the right target. We found out from prior pilot studies that the average search task completion time was 3.5 minutes per task and we have 4 conditions, we don't require the whole experiment to exceed the recommended time, 60 minutes-90minutes [43].

Navigation

In navigation task, participants are given a target with spatial location around Copenhagen area. Targets are initially displayed as red markers showing that it cannot be manipulated. When the appropriate zoom level reaches, the target turns into green informing that tasks can be completed by clicking on the bounding box of the target.

Search-I

In designing the search task, we referred various empirical studies such as [3, 12, 13, 17]. In this studies, search and compare tasks have targets with numerical and/or textual values, and participants are required to compare or search targets according to the task specifics. Although this task types are widely adopted, they introduce additional mental effort which could potentially take considerable amount of time. We have chosen color based search tasks for this experiment. In search-I task, participants are given 10 targets initially colored as blue markers. When certain zoom level reaches, target's color changes into red except for four of the targets. This four targets turns into green after certain zoom level reaches. The task here is to find out one of the four targets. The task will be completed when participants clicked on the bounding box of this target, as shown in figure 7.2

Figure 7.2, search task: (A) search target markers displaying 10 targets, (B-C) search targets before and after certain zoom level reaches, respectively. Green markers are targets, and red markers show false targets in search tasks.

Figure 7.3, route tracing task: targets are displayed on top of train station in Copenhagen area and are connected by orthographic lines.

7.1.1 Search-II

In Search-II task, participants will be provided textual landmark description of a natural feature from the map such as lake, park, zoo, etc. The task here is to find and locate targets and call out to the experimenter.

Route Tracing

In route tracing task, 10 markers are displayed on top of 10 train/metro stations in Copenhagen area, and train route is displayed by connecting the markers using orthographic line geometry as shown in figure 7.3. The markers are initially located few pixels away from the actual train station location. The task here is to drag and put the markers onto the nearest train/metro station.

PARTICIPANTS

For this experiment 10 male and 2 female of age ranging from ?? to ?? participated in the experiment. Six of them are recent graduates from economics and computer science department of university of Copenhagen. The remaining are professionals in IT and natural science area. From the preliminary interview, we found out that most of them are new to large wall displays and proximity based interaction. However, they are familiar with zoom+pan interface on ordinary desktop displays.

DATA GATHERING

For all navigation conditions and experiment tasks automatic data gathering method have been used. Task completion time is recorded for every targets in every tasks automatically by enforcing participants to complete tasks with 100% accuracy. 3D position and gaze location is recorded every second for every condition and tasks throughout the experiment period. Gaze-display boundary collision is also recorded for every frame in the simulation time. That is, once in 0.04 seconds for average frame rate of 25 FPS.

APPARATUS

To conduct this empirical study, we have developed a semantic zoom+pan interface by using opensource projects such as OSG [36] and osgEarth [40] for

2D/3D visualization and on-the-fly terrain rendering based on the openstreetmap [39] tile overlays. The screen is a tiled wall-size display consisting of 12 projectors arranged in a 4x3 matrix. Each projector has a resolution of 1920x1080, providing a total resolution of 7680x3240 or approximately 24.8 Megapixels.

PROCEDURE

In the beginning each participant will be briefed about the purpose of the study, the interfaces and the different tasks. Then, participants will start using the interfaces with each of the tasks until they feel they are comfortable with the interfaces and confident to proceed with the experiments. Appendix-A shows the experiment guide adopted from Lazar et al [43] for the empirical study discussed in this chapter.

CHAPTER 8 -EXPERIMENT ANALYSIS

INTRODUCTION

In chapter-7 empirical study design of this thesis project has been discussed and based on prior discussions and earlier research works, six hypotheses were made. In this chapter, analysis of the empirical study is presented. In this section outcome of the analysis is summarized with respect to the hypotheses made in earlier chapter.

Hypothesis – 1: *Since Head movement is required in Gyro/Hybrid navigation condition; we will not get significant increase in the amount of head rotation for proximity based navigation techniques.*

Analysis – 1: The experiment was able to show a main effect for navigation techniques and task types for the amount of head movement. From the follow up pairwise analysis Gyro resulted significant amount of head/gaze movement compared to Gaze and Absolute. However, no significant mean difference was found between Gaze and Absolute.

Hypothesis – 2: *Since Head movement is required in Gyro/Hybrid navigation condition; subjects will not experience significant increase in the amount of neck fatigue in using proximity based navigation techniques.*

Analysis – 2: From the ANOVA, no significant main effect was found for navigation technique and task types. The interaction effect is also not significant. Therefore, there is no significant increase of neck fatigue in using proximity based navigation techniques (Gaze, Absolute and Relative).

Hypothesis – 3: *Since Gyroscopic mouse drives multi-scale navigation in Gyro/Hybrid navigation technique; we will get significant increase in the amount of bodily movement for proximity based navigation techniques. Hence, participants will experience significant reduction in the amount of Arm fatigue.*

Analysis – 3: For bodily movement, two factors were analyzed; physical movement distance and movement range. For physical movement distance a main significant effect was found for both navigation technique and task type. A significant interaction between navigation technique and task type was also found. For physical movement range a main effect was found for both navigation technique and task type. A significant interaction between navigation technique and task type was also found. For Arm fatigue a significant main effect was found for navigation technique. A follow-up pairwise comparison showed that Gaze (1.875), absolute (1.8) and Relative (1.752) significantly reduced amount of arm fatigue compared to Gyro(4.0).

Hypothesis – 4: *Since there is significant amount of bodily movement for proximity based navigation techniques, subjects will be engaged in performing tasks, their spatial and motor memory will be utilized. Therefore, proximity based navigation technique will have less task completion time.*

Analysis – 4: A main significant effect for both navigation technique and task type was found. From the follow up pairwise comparison Gaze based (M=37.81s) and Absolute (M=36.51s) navigation techniques significantly outperform Gyro (M=59.39). However, no significant mean difference was found between relative navigation and the rest of the navigation techniques, nor between Gaze and Absolute.

Hypothesis –5: *Since target acquisition and multi-scale navigation are decoupled in proximity based navigation techniques, participants will have a chance to make the two actions simultaneously. Therefore, the proposed navigation techniques will primarily outperform Gyro/hybrid based navigation for tasks that benefit from this characteristic; one prominent example is train route tracing task.*

Analysis – 5: A main statistical significance in navigation techniques and task type was found. However, there was no significant interaction effect between navigation technique and task type. This means that in all of the task types, Gaze and Absolute navigation techniques outperform Gyro method in task completion time.

Hypothesis –6: *Because of a complete one to one correspondence in motor-to-display space mapping, absolute navigation will have less mental effort to complete the tasks compared to the other proximity based navigation techniques.*

Analysis – 6: From the two-way RMANOVA applied on mental effort, no significant main effect was found for navigation technique and task type. The interaction effect was also not significant.

PERFOMRANCE ANALYSIS

There are two independent variable in this study, Navigation technique (Gyro, Gaze, Absolute, and Relative) and task type (Navigation, Search-I, Tracing and Search-II). Table-8.1 shows the means and standard error for task completion time for the two primary effects. Absolute performs the best among the four navigation techniques in term of completion time (36.51s). Gyro showed the poorest performance (59.39s).

Table-8.1, *Mean and STD. error of task completion for the two primary factors (navigation technique and task types)*

	Navigation Technique				Task type			
	Gyro	Gaze	Absolute	Relative	Navigation	Search-I	Tracing	Search-II
Mean	59.39	37.81	36.51	44.14	15.97	28.74	88.53	44.61
Std.Err	5.16	2.88	2.39	2.19	1.3	1.97	9.19	4.0

Table-8.2, *Mean(M) and Standard Deviation (SD) of task completion time in (M, SD) format for all 16 Navigation technique X task type conditions*

		Task type			
		Navigation	Search-I	Tracing	Search-II
Navigation Technique	Gyro	(22.45, 10.56)	(44.49, 12.67)	(113.33, 51.95)	(57.32,25.22)
	Gaze	(10.73, .85)	(22.43, 11.15)	(74.9, 33.15)	(43.08, 19.24)
	Absolute	(13.22, 2.07)	(19.94, 5.72)	(77.37, 31.04)	(35.5, 14.85)
	Relative	(17.46, 4.84)	(28.1, 10.29)	(88.45, 23.79)	(42.55, 12.82)

A two-way repeated measure ANOVA was performed on performance times with navigation technique and task types as independent variables. From the analysis, we found a main significant effect for both navigation technique and task type: $(\mathrm{F}(3,27)\ = 18.921,\ p\ <\ 0.001)$ and $(\mathrm{F}(3,27)\ = 38.467,\ p\ <\ 0.001)$, respectively. From Bonferroni post hoc pairwise comparison, Gaze based (M=37.81s) and Absolute (M=36.51s) navigation techniques significantly outperform Gyro (M=59.39) $(P < 0.05)$. However, no significant mean difference was found between relative navigation and the rest of the navigation techniques$(P > 0.05)$, nor between Gaze and Absolute $(P > 0.05)$. Figure-8.1-(A) shows mean performance and standard error for the four navigation techniques. Gaze and Absolute are significantly faster than Gyro condition.

A main statistical significance in navigation techniques and task type was found. However, there was no significant interaction effect between navigation technique and task types $(\mathrm{F}(9,81)\ = 1.266, p > 0.05)$. This means that in all of the task types, Gaze and Absolute navigation techniques outperform Gyro method in task completion time, figure-8.1-(B). There are three possible reasons behind this.

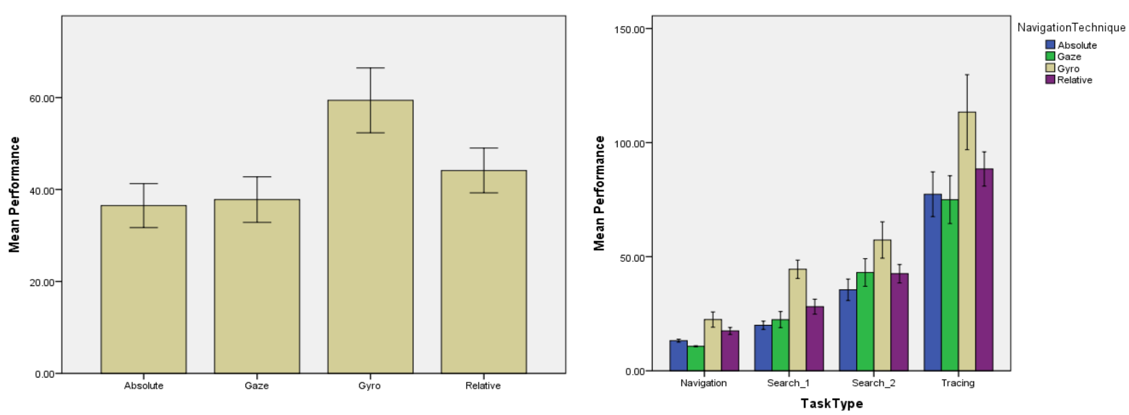


Figure-8.1, *(A) Mean performance and standard error for the four navigation techniques, (B) Mean performance and standard error for the four navigation techniques within the four task types*

First, Embodied resources such as motor and spatial memory are more utilized for proximity based navigation techniques than Gyro method since multi-sale navigation is designed to respond to different bodily movements. Embodied interactions have been reported to be one of the main factors in performance improvements in performing spatial tasks on Large Wall Displays [3, 12, 13, 17, and 41].

Second, most of participants are observed to perform "zoom-around" operation. That means, they prefer to perform zooming and panning at the same time. Since Gaze and Absolute navigation techniques follow Absolute mapping of motor-to-display space for zooming operation, there is a possibility that multi-scale navigation speed can be controlled by physical movement in the motor space.

Third, target acquisition and multi-scale navigation are decoupled for proximity based navigation techniques (Gyro, Gaze and Relative) unlike for Gyro method where the two operations can only be performed separately. For example, for route tracing task four of the participants are observed to manipulate the task targets (target-acquisition) while walking towards to the display (multi-scale navigation). This resulted 33.89% and 31.71% performance improvements for Gaze and Absolute navigation, respectively.

Relative navigation on the other hand doesn't significantly outperform Gyro method in task completion time. One of the reasons might be the introduction of extra physical movement required to orient oneself relative to the hotzone. Please refer the next section for physical movement analysis.

PHYSICAL MOVEMENT ANALYSIS

Earlier research works such as North et al [12, 13] associated physical movement as one of factors that lead to improvement of task performance for spatial tasks on large wall displays. In this section we analyze the amount of physical movement associated with each experiment conditions (navigation technique X task types).

We have treated participant's physical movement into two; head rotation and bodily movement. Head rotation is one of the three head movements (pitch, yaw and roll) that potentially changes gaze location on the display. And physical bodily movement is considered as any kind of bodily movement (translation) in the display room.

Physical Bodily Movement

For all experiment conditions, there is no factor (such as keyboard, table, etc…) that restricts bodily movement (untethered environment). Hence, participants are expected to perform free physical bodily movement for all conditions.

To analyze the amount of physical bodily movement, we have tracked participant's 3D location in the room and mapped X, Y and Z axes to the display where the origin is assumed to be the left bottom edge of the display screen, figure-8.2.

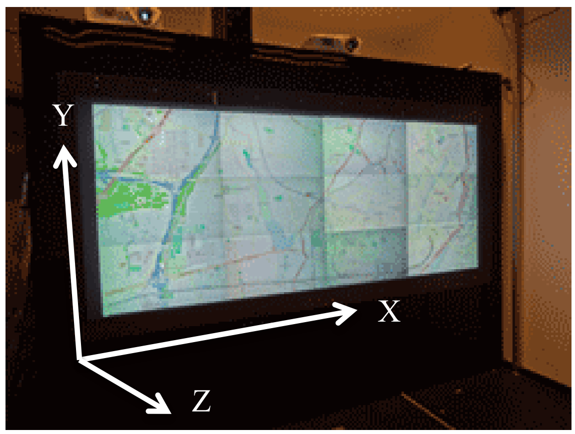


Figure-8.2 *illustration of X, Y and Z axes with relation to the*

The X axis starts at the left bottom edge and runs parallel to the display. Participants moving along X axis will walk parallel to the display. This type of movement is associated to horizontal physical panning (for Gyro condition) and horizontal virtual panning (for absolute condition). Y axis runs along the height of the display and is associated to physical panning in the vertical direction. Movement along this axis is assumed to be negligible since participants have not tried to jump or crouch to perform any of the tasks, see figure-8.3. From figure-8.3 head pose (height) looks smoother than Gaze and Absolute, this is from the use of gaze based panning for vertical direction. For relative navigation, there seems to be more variation on head pose. This is because participants made minor leaning while stepping out of the hotzone.

Z axis runs perpendicular to the display. Movement along Z axis is related to physical zooming (for Gyro condition) and virtual zooming (for Gaze, Absolute and Relative conditions)

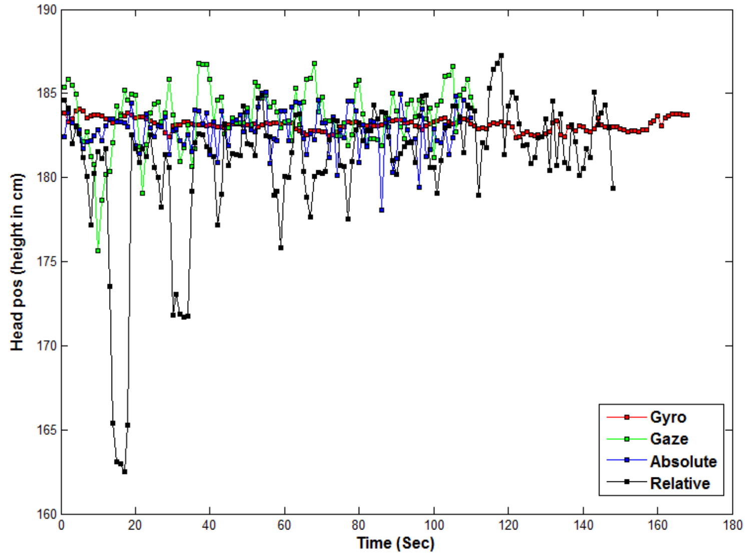


Figure-8.3, *Head position (Y-axis) information for one of the participants performing navigation task using the four navigation techniques*

To quantitatively analyze physical bodily movement, Ball et al [13] have treated physical bodily movement into two; Movement range and total physical movement distance. In this experiment analysis we adopt the same approach except that we analyzed the *true* movement area usage by extracting convex hull from participant's location coordinate, instead of calculating $(\max \text{Pos} - \min \text{Pos})$, as in the case of Ball et al [13].

Physical movement distance was calculated as Euclidean distance of participant's location in the room (in terms of X, Z axes, since movement along Y axes assumed to be negligible.). To analyze true physical movement, we have to make sure that we counted true physical movement, not jitter. One way to remove jitter effect is to use path simplification algorithms. However, most path simplification algorithms such as Douglas-Peucker [42] assumed the path as polylines (no self-crossing allowed in the path). To work around this, physical location was registered every second, instead of every frame rate (0.04 second). This to some extent reduces the amount of jitter in the total distance calculated.

Table-8.3 shows the mean and standard error for physical movement distance for the two factors. Gaze based navigation resulted the highest amount of physical movement distance (2439.2cm) among the four navigation techniques, while Gyro navigation resulted the least amount of physical movement distance (690.3cm). Table-8.4 shows means and standard deviation of physical movement distance for all 16 experiment conditions. Figure- 8.4 shows the general trend of physical movement distance for the different navigation technique and task type combinations.

Table-8.3, *Mean and STD. error for physical movement distance in terms of the two primary factors (navigation technique and task types)*

	Navigation Technique				Task type			
	Gyro	Gaze	Absolute	Relative	Navigation	Search-I	Tracing	Search-II
Mean	690.3	2439.2	2230.5	2411.0	2705.8	2612.5	646.5	1806.2
Std.Err	128.8	176.5	97.5	167.3	158.5	141.8	95.8	216.0

Table-8.4, *Mean (M) and Standard Deviation (SD) of physical movement distance in (M, SD) format for all 16 Navigation technique X task type conditions*

		Task type			
		Navigation	Search-I	Tracing	Search-II
Navigation Technique	Gyro	(607.1, 412.8)	(718.2, 611.0)	(341.9, 259.9)	(1093.9,615.2)
	Gaze	(3271.4, 719.6)	(3524.0, 1300.7)	(677.4, 563.4)	(2284., 1154.9)
	Absolute	(3508.5, 648.7)	(3014.8, 817.9)	(612.9, 354.2)	(1785.7, 650.4)
	Relative	(3436.3, 801.5)	(3193.0, 1229.4)	(953.8, 440.2)	(2061.0, 779.6)

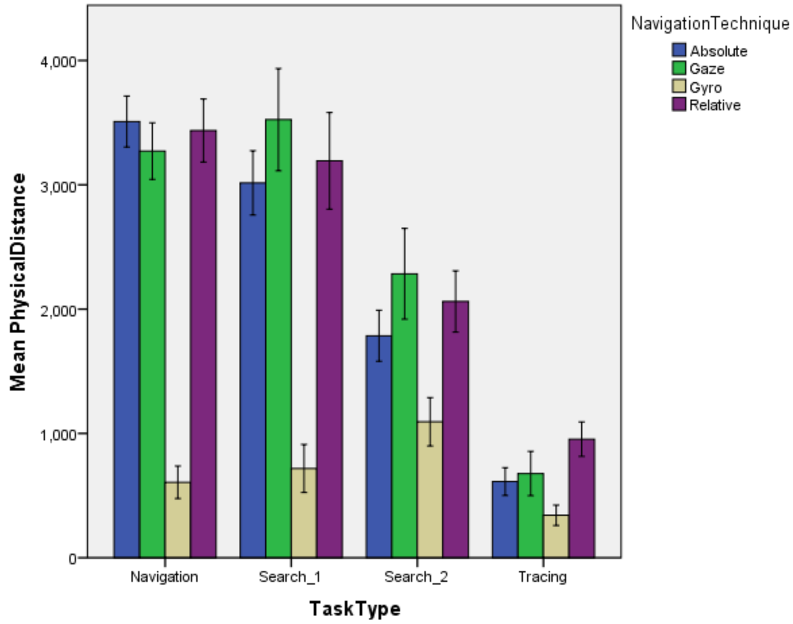


Figure-8.4, *Average physical Distance traveled with Navigation, Search-I, Search-II and route tracing tasks using the four navigation Techniques. Error bars shows standard error of the mean*

To analyze physical bodily movement, a two-way repeated measure ANOVA was performed on physical movement distance with navigation techniques and task type as independent variables. From the analysis, a main significant effect was found for both navigation technique and task type: $(F(3,27)\ = 53.227,\ p\ <\ 0.001)$ and $(F(3,27)\ = 49.08,\ p\ <\ 0.001)$, respectively. A significant interaction between navigation technique and task type was also found, $(F(9,81)\ = 8.77,\ p\ <\ 0.001)$.

With the task type, a post hoc Benferroni pairwise comparison was applied. From the pairwise comparison, all task types are significantly different from each other, $p\ <\ 0.05$ (with the exception of Navigation-Search-I, p=1.0 and Search-I-Search-II, p=0.052).

As a follow-up to the RMANOVA, a simple main effect 1-way repeated measure ANOVA was performed for each tasks with navigation techniques as independent variable, table-8.5.

Table-8.5, *statistical results on physical movement distance*

	Main effect of navigation technique
Navigation	$F(3,27) = 79.048,\ p < 0.001$
Search-I	$F(3,27) = 14.292,\ p < 0.001$
Route tracing	$F(3,27) = 5.615,\ p < 0.05$
Search-II	$F(3,27) = 9.139,\ p < 0.01$

For navigation task, Gaze (3271.36cm), Absolute (3508.54cm) and Relative (3436.28cm) resulted significantly larger amount of physical movement distance compared to Gyro (607.1cm), $p < 0.05$.

For Search-I task, Gaze (3524.01cm), Absolute (3014.83cm) and Relative (3193.03cm) resulted significantly larger amount of physical movement distance compared to Gyro (718.17cm), $p < 0.05$.

For Search-II task, Gaze (2284.0cm) and Relative (2061.03cm) resulted significantly larger amount of physical movement distance compared to Gyro (1093.99cm), $p < 0.05$. For this task type, Gyro navigation resulted increased physical movement distance compared to the rest of task types. One possible reason might be the associated semantic zooming requirement for this task. Participants are required to analyze the map content from overview to detail, unlike the other tasks where the targets are artificial markers annotated on the map. This makes the participants to actively walk around in the room; by performing multi-scale navigation using Gyro mouse and physical zooming by walking towards-to/away-from the display.

For Route Tracing task Absolute (612.96cm) and Relative (953.83cm) resulted significantly larger amount of physical movement distance compared to Gyro (341.93cm), $p < 0.05$.

For all task types, Relative Navigation resulted significantly large amount of physical movement distance compared to Gyro. One possible reason for this is from the design decision we made for hotzone area in relative navigation. If we choose smaller hotzone area, participants will face difficulty in orienting themselves relative to the hotzone. Therefore, we have chosen 50cmX50cm area. However, this required the participants to make more physical movement to get in/out of the hotzone. And at some point during the experiment, three of the participants were observed to walk side to side perpendicular to the display (for zooming) instead of stepping few inches from the hotzone. Figure-9.4 shows top down view of the display room, where the X-axis represents the display screen.

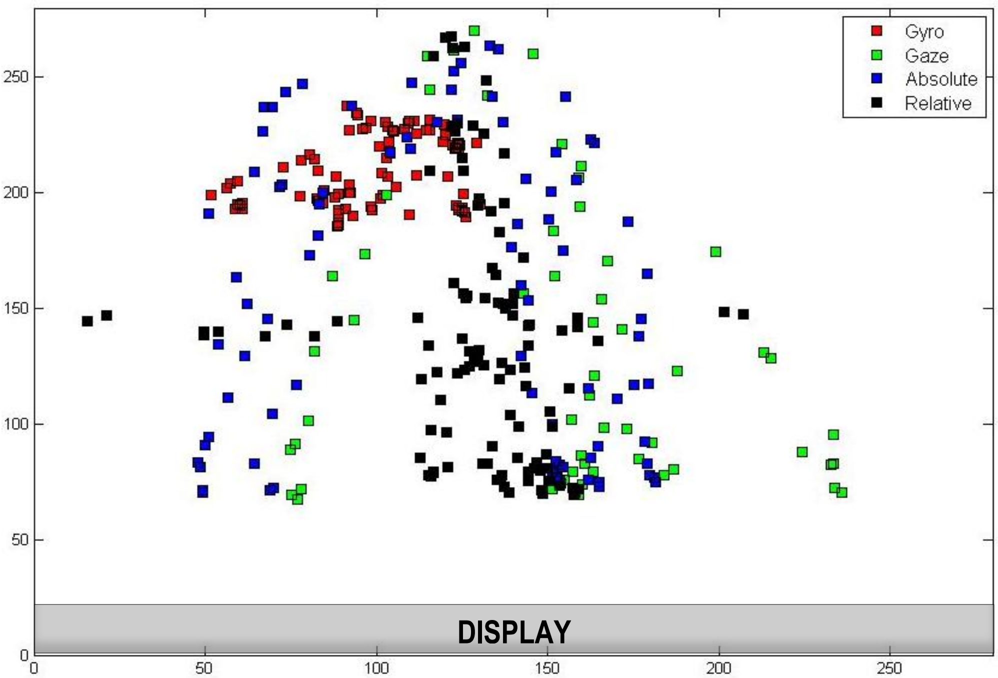
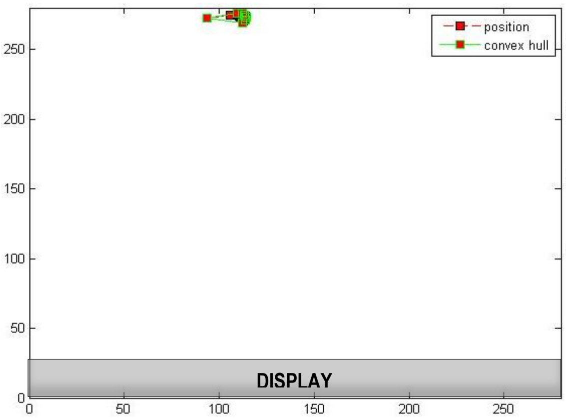
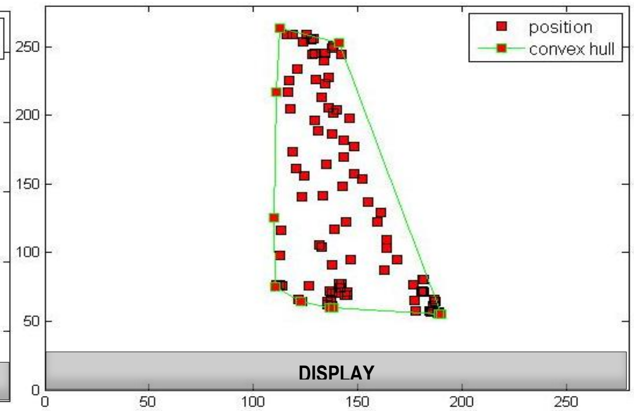


Figure-8.5*, physical locations for the first participant performing navigation task using Gyro, Gaze, Absolute and Relative navigation techniques.*

Physical movement range is considered as the range of physical area usage. To properly analyze the true physical movement range, convex hull of movement range have been extracted from participant's location coordinate using Graham's scan algorithm [49-50]. The result is a convex polygon approximating participant's range of physical area usage while performing experiment tasks. Figure-8.6-(A-B) shows movement range of one of the participant performing navigation task on Gyro and Gaze condition, respectively.



A)



B)

Figure-8.6*, Movement range of one of the participant performing navigation task on (A) Gyro, (B) Gaze conditions*

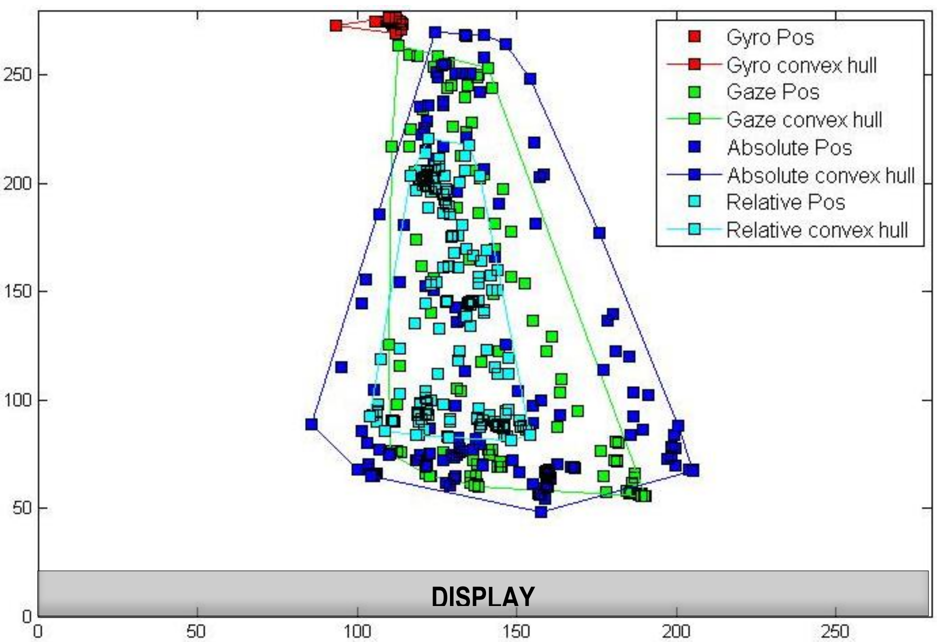


Figure-8.7*, Movement range of one of the participant performing navigation task for all navigation techniques*

Table-8.6 shows the mean and standard error for physical movement range for the two factors. Gaze based navigation resulted the highest amount of physical movement range (171.9m^2) among the four navigation techniques, while Gyro navigation resulted the least amount of physical movement range (37.1m^2).

Table-8.7 shows means and standard deviation of physical movement range for all 16 experiment conditions.

Table-8.6, *Mean (in meter²) and STD. error for physical movement range in terms of the two primary factors (navigation technique and task types)*

	Navigation Technique				Task type			
	Gyro	Gaze	Absolute	Relative	Navigation	Search-I	Tracing	Search-II
Mean	37.1	171.9	156.5	116.0	134.8	141.1	53.7	151.9
Std.Err	14.9	13.4	10.2	11.6	9.0	9.7	10.1	20.8

Table-8.7, *Mean (M) and Standard Deviation (SD) of physical movement range in (M, SD) format for all 16 Navigation technique X task type conditions*

		Task type			
		Navigation	Search-I	Tracing	Search-II
Navigation Technique	Gyro	(15.96, 31.1)	(22.8,42.3)	(15.93, 34.8.5)	(93.4, 95.63)
	Gaze	(199.7, 48.9)	(207.1,39.57)	(71.46,52.0)	(209.2, 96.8)
	Absolute	(193.1, 35.3)	(182.6, 70.2)	(75.7,73.5)	(174.6, 58.7)
	Relative	(130.1,37.8)	(151.7,62.8)	(51.6,24.9)	(130.5, 83.7)

To analyze physical movement range, a two-way repeated measure ANOVA was performed on physical movement range with navigation techniques and task type as independent variables. From the analysis, a main significant effect was found for navigation technique ($F(3, 27) = 39.54$, $p < 0.001$) and task type ($F(3, 27) = 17.54$, $p < 0.001$). Significant interaction between navigation technique and task type was also found, ($F(9, 81) = 4.631$, $p < 0.01$). Simple main effect 1-way repeated measure ANOVAs were conducted for each tasks with navigation techniques as independent variable, table-8.8.

For navigation task, Gaze (199.7m^2), Absolute (193.1m^2) and Relative (130.1m^2) resulted significantly larger amount of physical movement range compared to Gyro (15.9m^2), $p < 0.05$. For Search-I task, Gaze (207.1m^2) and Relative (151.7m^2) resulted significantly larger amount of physical movement range compared to Gyro (22.8m^2), $p < 0.05$. For Route Tracing task, Gaze (71.5m^2) and Relative (51.6m^2) resulted significantly larger amount of physical movement range compared to Gyro (15.9m^2), $p < 0.05$.

Table-8.8, *statistical results on physical movement range*

	Main effect of navigation technique
Navigation	$F(3, 27) = 7.355,\ p < 0.05$
Search-I	$F(3, 27) = 4.417,\ p < 0.05$
Route tracing	$F(3, 27) = 4.159,\ p < 0.05$
Search-II	$F(3, 27) = 1.758,\ p > 0.05$

Head Rotation

As part of participant's physical movement analysis, participant's head rotation was also tracked and registered every frame rate (0.04sec). Head rotation is one of the three head movements (pitch, yaw and roll) that potentially changes gaze location on the display. Approximate gaze location was represented by resizable dragged cursor for all experiment conditions. It is mainly used for "zoom around" operation for all navigation techniques (except Gyro).

Participant's head rotation can result either of the two states; first, by repositioning it to the appropriate point on the map it is used for "zoom-around" operation. Second, there is gaze-display boundary collision, which can be intentional as in the case of gaze based navigation technique (used for multi-directional panning), or it can be completely unintentional. This tells us that the amount of head rotation can be approximately computed from the amount of gaze movement on the display and gaze-display boundary collisions. Therefore, we have independently tracked and registered gaze movement and gaze-display boundary collisions as dependent factors for all experiment conditions.

The total *Gaze distance* was calculated as Euclidean distance from each gaze points (pixels) on the display. In this analysis we will report gaze distance in terms of Kilopixels (KP). Figure 8.8 shows approximate gaze locations represented as points on the 7680x3240 wall display.

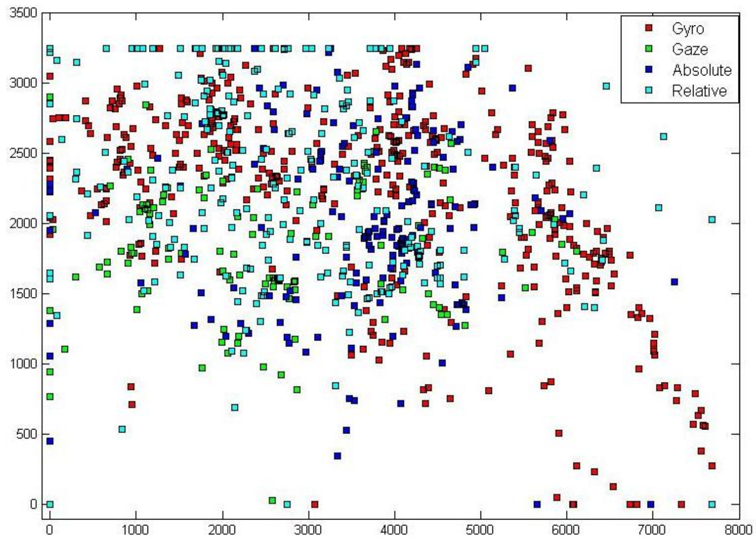


Figure-8.8, *Gaze points for one of the participant performing navigation task.*

After running two-way repeated measure ANOVA, a significant main effect was found for navigation techniques, $(\mathrm{F}(3,27) = 17.79,\ p < 0.001)$ and task types, $(\mathrm{F}(3,27) = 23.607,\ p < 0.001)$. From the follow-up pairwise comparison on navigation techniques, Table-8.9, Gyro (134.57KP) resulted significant amount of gaze movement compared to Gaze (87.43KP) and Absolute (82.77KP). However, no significant mean difference was found between Gaze and Absolute, $p > 0.05$.

Table-8.9, *Mean and STD. error for gaze distance in Kilopixels*

	Navigation Technique			
	Gyro	Gaze	Absolute	Relative
Mean	134.57	87.43	82.77	106.30
Std.Err	8.0	5.91	5.84	6.95

This result supports the first hypothesis of this empirical study in that there is no significant increase in the amount of head rotation (gaze movement) for the proposed proximity based navigation techniques. Instead, gaze movement using Gyro method found to be significantly larger than Gaze and Absolute methods.

ANALYSIS OF THE QUESTIONAIRES

After the completion of each tasks for each navigation techniques, participates were given a questionnaire to assess quality of the technique and provide scaled response for different type of fatigue involved in the task. After the experiment is done, participants were given another questionnaire to rank the navigation techniques and provide general comments about their experience in using the navigation techniques.

User rating

At the end of the experiment, participants were given questionnaire-2 to rank the navigation techniques based on their preference. They were expected to rank the techniques from scale 1-4, 1 being the best and 4 being the worst. Table-8.10 shows mean ratings of navigation techniques and figure 8.9 shows user preference for navigation techniques.

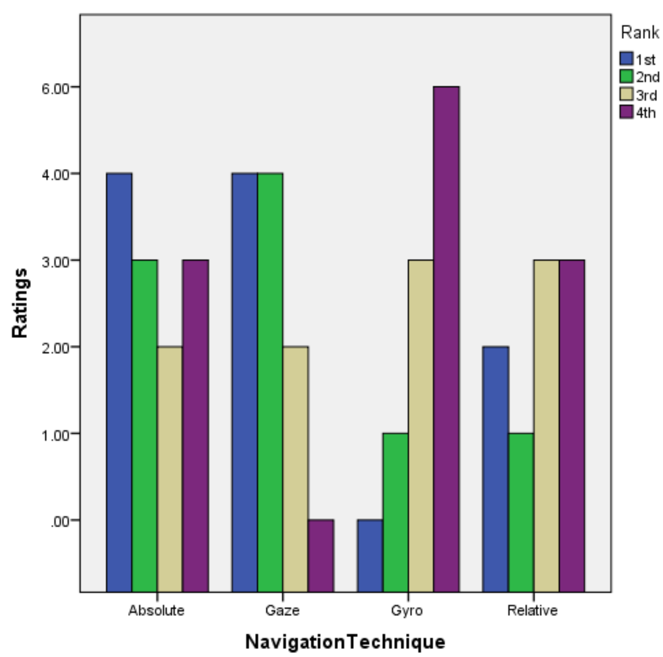


Figure-8.9, *user preference for navigation techniques*

Table-8.10, *Mean ranks for the four navigation techniques*

Gaze	Absolute	Relative	Gyro
3.2	3.0	2.3	1.5

Running one-way RMANOVA shows significant difference for mean subjective ratings, $F(3, 27) = 4.975,\ p < 0.05$. Follow-up pairwise comparison was made to see significant difference between each navigation technique, Table-8.11. Gaze(3.2) and Absolute(3.0) outperform Gyro(1.5) on user satisfaction, $p < 0.01$ and $p < 0.05$, respectively.

Table-8.11, *significances from 1-way RMANOVA, * indicates significant P value, and preferred navigation technique is marked with bold*

Gyro-**Gaze**	Gyro-**Absolute**	Gyro-Relative	Gaze-Absolute	Gaze-Relative	Absolute-Relative
0.002*	**0.04***	1.0	1.0	0.648	1.0

Arm and Neck Fatigue

The first questionnaire was partly designed to collect scaled response about Arm and Neck fatigue in doing the experiment tasks. Participants were provided with a Likert scale questions scaled from 1-9, 1 for negligible fatigue and 9 as very high amount of fatigue.

To statistically analyze the effect of navigation technique, task types and the possible interaction effect on *Arm fatigue*, a two-way RMANOVA was conducted on arm fatigue scaled response with navigation technique and task types as independent variables. Table-8.12 shows mean scaled response for amount of arm fatigue associated with each navigation techniques.

Table-8.12, *Mean scaled response of Arm fatigue for the four navigation techniques*

Gaze	Absolute	Relative	Gyro
1.875	1.80	1.752	4.0

From the ANOVA, a significant main effect was found for navigation technique, ($F(3,27) = 21.06,\ p < 0.001$). However, main effect of task type and its interaction effect with navigation technique were not significant, $p > 0.05$. A follow-up pairwise comparison showed that Gaze(1.875), absolute(1.8) and Relative(1.752) significantly reduced amount of arm fatigue compared to Gyro(4.0). Table-8.13 shows result of pairwise comparison and significance test.

Table-8.13, *pairwise comparison from 2-way RMANOVA, * indicates significant P value, and preferred navigation technique is marked with bold*

Gyro-**Gaze**	Gyro-**Absolute**	Gyro-**Relative**	Gaze-Absolute	Gaze-Relative	Absolute-Relative
0.002*	**0.001***	**0.008***	1.0	1.0	1.0

For *Neck Fatigue*, we have collected participant's scaled response using Likert scale questions in questionnaire-1. Table-8.14 shows mean scaled response for amount of neck fatigue associated with each navigation techniques.

Table-8.14, *Mean scaled response of Neck fatigue for the four navigation techniques*

Gyro	Gaze	Absolute	Relative
2.475	2.925	2.5	2.325

To statistically analyze the effect of navigation technique, task type and the possible interaction effect on Neck fatigue, a two-way RMANOVA was conducted. From the ANOVA, no significant main effect was found for navigation technique and task types, $p > 0.05$. The interaction effect is also not significant, $p > 0.05$. That means, there is no significant increase of neck fatigue in using proximity based navigation techniques (Gaze, Absolute and Relative) and this basically supports hypothesis-2 of this empirical study.

One possible reason for this result might be the association of neck fatigue with amount of head rotation (gaze movement distance). In section 9.2.2 the proposed navigation techniques didn't lead to increased gaze distance. In fact, there was a significant reduction in the amount of gaze distance compared to Gyro method. This possibly made the participants to experience relatively constant neck fatigue. Figure-8.10 shows mean scaled response of Arm and Neck fatigue for the four navigation techniques. *Significant reduction of arm fatigue* and similar (or *insignificant neck fatigue*) associated with the proposed navigation techniques (Gaze, Absolute and Relative) can be seen from figure-8.10.

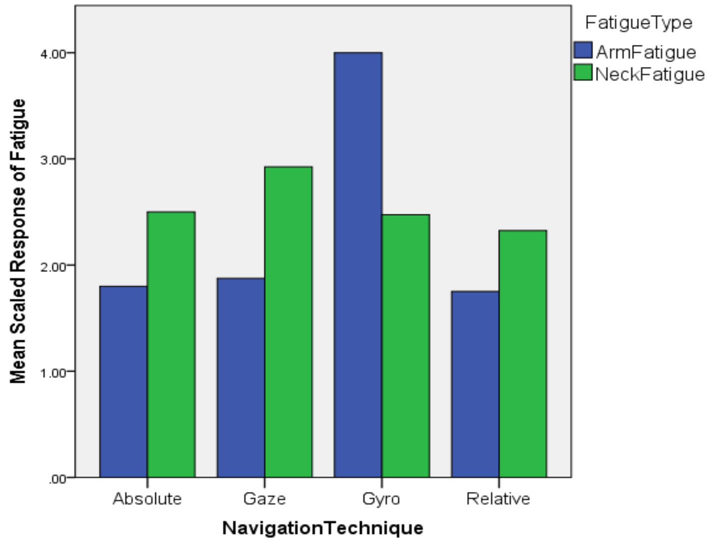


Figure-8.10, *Mean scaled response of Arm and Neck fatigue*

Physical and Mental effort

After the completion of every task for every navigation techniques, participants were provided with questionnaire-1. The questionnaire was designed partly to acquire scaled response from participants about the amount of physical and mental effort required to complete the tasks. The questions are designed as Likert scale questions with scale from 1-9, 1 as being negligible effort and 9 as very high mental/physical effort required to complete the tasks.

From the mean scaled response of *Physical Effort*, Table-8.15, participants experienced more physical effort for Gyro than any of the proposed techniques. To statistically analyze the effect of navigation technique and task types on *Physical Effort*, we run two-way RMANOVA on physical effort using navigation technique and task types as factors. From the ANOVA analysis, no significant main effect was found for Navigation technique and task type, $p > 0.05$. The interaction effect was also not significant, $p > 0.05$.

Table-8.15*, Mean scaled response of Physical Effort for the four navigation techniques*

Gyro	Gaze	Absolute	Relative
3.175	2.65	2.60	2.60

Since the navigation techniques were designed differently, we expected to see significant mean difference with *Mental Effort* required to complete tasks in the experiment. From the mean scaled response of mental effort associated with each navigation techniques, table-8.16, participants have experienced relatively higher mental effort required to complete tasks by using relative navigation. Gaze based navigation required the lowest mental effort to complete the tasks.

Table-8.16*, Mean scaled response of Mental Effort for the four navigation techniques*

Gyro	Gaze	Absolute	Relative
2.725	2.475	2.650	3.125

From the two-way RMANOVA applied on mental effort, no significant main effect was found for navigation technique and task type, $p > 0.05$. The interaction effect was also not significant, $p > 0.05$.

Because of the different design methods used for all navigation techniques, we expected significant mean difference of physical and mental effort required to complete tasks using the four navigation techniques. We have also expected that participants will experience less mental effort required to complete tasks using absolute navigation because of the one to one motor-to-display space mapping used for zooming and panning. However, the mental effort mean difference was found insignificant. Therefore, hypothesis-6 of this empirical study is rejected.

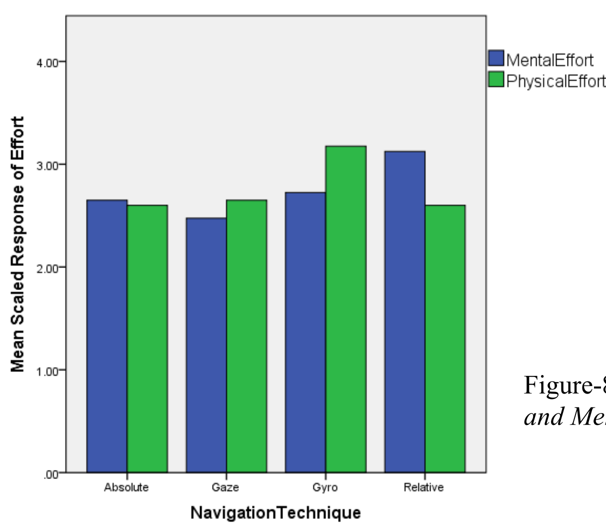


Figure-8.11, *Mean scaled response of Physical and Mental Effort*

EXPERIMENT CONCLUSION

The experiment showed various promising results for proximity based navigation techniques. First, a significant performance improvement for Gaze and Absolute navigation was found. Second, participants experienced significant reduction in arm fatigue for all proposed navigation techniques. Third, they also experienced near similar neck fatigue for all navigation conditions. Analyzing mental and physical effort load, no significant mean difference was found.

EXPERIMENT LIMITATIONS

Eventhough promising results was found from the experiment performed on the 10 subjects with experiment settings and task specifics, there are certain limitations that worth considering.

Participant size

10 subjects participated on the experiment. However, it is important to include more subjects to increase statistical power.

Participants experience with gyroscopic mouse

9 out of the 10 participants had no or limited experience in using Gyroscopic mouse. This might have significant effect on task performance and user satisfaction for Gyro navigation. Therefore, participant should be carefully selected to explain away prior experience factor.

Task types

We have used two types of search which were based on artificial markers (Search-I) and natural feature (Search-II). Eventhough this task types have been used in various empirical studies, it is still important to consider tasks with little stochastic effects (for example comparison tasks). For Gyro condition increased mean physical distance was observed for Search-II task, this might be because of task nature as it requires different perception of the map to find the right feature on the map. Tasks which benefit from physical navigation should be included for similar empirical studies.

CHAPTER 9 - CONCLUSION

Various research works empirically presented the benefit of display size for various spatial tasks [3, 12, 13, 41]. High resolution large wall displays improves task performance and user satisfaction over their smaller counterparts. The main reason behind significant performance improvement was the use of embodied resources such as motor memory, peripheral vision, optical flow, focal attention, spatial memory and the opportunity of making physical navigation. Eventhough physical navigation outperforms virtual navigation for visualization intensive spatial tasks such as pattern finding [3, 12], virtual navigation is still required as datasets can be several orders of magnitude and are too large to fit on large wall displays. Therefore, research works on multi-scale navigation for wall displays should consider varies opportunities to link embodied resources and multi-scale navigation in a seamless fashion. This thesis introduces three proximity based multi-scale navigation techniques for wall displays. Based on the resource required to perform virtual navigation and mapping of motor space to display space, three navigation techniques were proposed and implemented; Gaze, Absolute and Relative navigation techniques.

The empirical study showed optimistic result for proximity based navigation techniques. Eventhough physical navigation was partly supported for the proposed navigation techniques, promising results from the empirical study was found suggesting the benefits of proximity based navigation over hybrid navigation using gyroscopic mouse. From the experiment significant performance improvement for Gaze and Absolute navigation was found. Participants experienced significant reduction in arm fatigue for all proposed navigation techniques. They also experienced near similar neck fatigue for all navigation conditions. After analyzing mental and physical effort load, no significant mean difference was found among the four navigation techniques.

FUTURE WORKS

Eventhough the proposed navigation techniques enable multi-scale navigation using bodily movement for wall displays, there are certain improvement to be made and potential future works to be considered.

Empirical study

Eventhough participants were allowed to make free bodily movement, most of them were observed to stand still and perform tasks on Gyro/Hybrid navigation. This navigational preference resembles virtual navigation setup discussed in chapter-5. However, few participants started to move around especially for Search-II task. Therefore, one possible future work would be to conduct an experiment to evaluate task performance for virtual navigation with hybrid/Gyro navigation and proximity based navigation techniques.

Workaround to vertical panning problem

As discussed in chapter-6, there is vertical panning problem in using the three proximity based navigation techniques. One possible solution would be to introduce uni-manual techniques[19], so that the free hand will perform vertical panning gestures while the other hand uses Gyroscopic mouse for pointing.

Incorporating physical navigation

The three navigation techniques provide limited physical navigation. To include physical navigation with multi-scale navigation for wall displays, one possible future research work would be to design location independent navigation techniques, so that pure physical and virtual navigation can be performed on demand.

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APPENDIX – A
PROXIMITY BASED NAVIGATION TECHNIQUE FOR WALL DISPLAYS
EXPERIMENT GUIDE

1. Ensure the system, the tracker and other necessary devices are ready for the experiment
2. Greet the participants
3. Introduce the purpose of the study and the procedures or alternatively hand out experiment introductory documentation from Appendix-D
4. Assign the participant to any of the four groups from Table-1.0-C and find out the order of experiment condition (navigation technique) they have to follow.
5. Start recording on camera
6. For each navigation technique
   A. Explain how the navigation techniques works
   B. Let the participant practice how to use the navigation techniques and complete a single task from each task types using training dataset, let them use the techniques until they feel like they are comfortable but not more than 5 minutes
   C. Assign the participant to any of the four groups from Table-2.0-C and find out the task order they have to follow
   D. Assign the participant to any of the four groups from Table-3.0-C and find out the dataset order they have to use
   E. Hand the participant a printout task description
   F. Repeat from E until all tasks have been completed
   G. Give out questionnaire-1 to participant
7. Debriefing session
8. Give out questionnaire-2 to participant
9. Stop recording on camera

APPENDIX – B

QUESTIONNAIRE-1

Participant ID: ___________

Age: ___________

Sex: ☐ Male ☐ Female

Height: ___________

Navigation technique and Task type

	Gyro	Gaze	Absolute	Relative
Navigation	☐	☐	☐	☐
Tracing	☐	☐	☐	☐
Search-I	☐	☐	☐	☐
Search-II	☐	☐	☐	☐

The navigation technique was

	1	2	3	4	5	6	7	8	9	
wonderful	☐	☐	☐	☐	☐	☐	☐	☐	☐	terrible
very easy	☐	☐	☐	☐	☐	☐	☐	☐	☐	very difficult
pleasant	☐	☐	☐	☐	☐	☐	☐	☐	☐	frustrating
very comfortable	☐	☐	☐	☐	☐	☐	☐	☐	☐	very uncomfortable
flexible	☐	☐	☐	☐	☐	☐	☐	☐	☐	rigid
fun	☐	☐	☐	☐	☐	☐	☐	☐	☐	boring

Arm Fatigue

	1	2	3	4	5	6	7	8	9	
None	☐	☐	☐	☐	☐	☐	☐	☐	☐	Very high

Neck Fatigue

	1	2	3	4	5	6	7	8	9	
None	☐	☐	☐	☐	☐	☐	☐	☐	☐	Very high

Physical effort required to use the technique was

	1	2	3	4	5	6	7	8	9	
None	☐	☐	☐	☐	☐	☐	☐	☐	☐	Very high

Mental effort required to use the technique was

	1	2	3	4	5	6	7	8	9	
None	☐	☐	☐	☐	☐	☐	☐	☐	☐	Very high

Other comments:

QUESTIONNAIRE-2

Participant ID: ___________

Age: ___________

Sex: ☐ Male ☐ Female

Height: ___________

Please prioritize the four navigation technique on a scale from 1-4, 1 is best and 4 is worst

___________ Absolute

___________ Gyro

___________ Gaze

___________ Relative

How much experience do you have using a mouse?

None 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ Very high

How much experience do you have using gyroscopic mouse?

None 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ Very high

How much experience do you have viewing large visualizations on wall displays?

None 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ Very high

How much experience do you have using map applications or zoom-pan interfaces?

None 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ Very high

Other comments

APPENDIX – C

EXAMPLE LATIN SQUARES

Table-1.0-C, Latin square for randomizing Navigation Technique order

	Group-1	**Group-4**	**Group-3**	**Group-2**
Period 2	Gyro	Absolute	Gaze	Relative
Period 4	Gaze	Gyro	Relative	Absolute
Period 1	Relative	Gaze	Absolute	Gyro
Period 3	Absolute	Relative	Gyro	Gaze

Table-2.0-C, Latin square for randomizing Task order

	Group-1	**Group-4**	**Group-3**	**Group-2**
Period 2	Search-2	Navigation	Search-1	Route tracing
Period 4	Navigation	Search-2	Route Tracing	Search-1
Period 1	Search-1	Route tracing	Navigation	Search-2
Period 3	Route Tracing	Search-1	Search-2	Navigation

Table-3.0-C, Latin square for randomizing Task targets

	Group-1	**Group-4**	**Group-3**	**Group-2**
Period 2	Databse-1	Databse-3	Databse-2	Databse-4
Period 4	Databse-2	Databse-1	Databse-4	Databse-3
Period 1	Databse-4	Databse-2	Databse-3	Databse-1
Period 3	Databse-3	Databse-4	Databse-1	Databse-2

APPENDIX – D
EXPERIMNET INTRODUCTORY MATERIAL

Introduction

Welcome! We have designed and implemented navigation techniques for wall displays and in this experiment we would like you try on four of our navigation techniques and complete four tasks. As part of data gathering we would like you to be video recorded, as it would give us invaluable information for latter analysis.

In this experiment we would like to evaluate two factors

1. Task completion time
2. Accuracy

Please note that we are not evaluating your performance. Therefore, try to complete the tasks as accurate as possible yet with less time.

Objective of the Experiment

The objective of this experiment is to evaluate the navigation technique we implemented by completing a series of tasks on geospatial datasets. You will be provided four navigation techniques and for each technique you will be given four types of tasks. In order to complete each of the tasks, you will be provided a gyroscopic mouse and a trackable hat.

Gyroscopic mouse

When trying to point and click on the display in mid-air, you will need to use a gyroscopic mouse as shown below. The mouse has an activation button at the bottom part. When the activation button clicked, the mouse will work in a way similar to ordinary mouse. The following picture also shows how to properly hold gyration gyroscopic mouse.

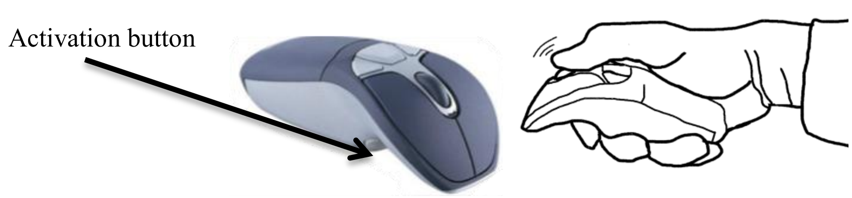

Figure 1., *gyroscopic*

In order to use the navigation techniques, you will be required to wear the trackable hat, figure 2. Please wear the hat before the experiment task begins and make sure that it fits you well. When experiment tasks started you will notice two circles. The inner circle as crossed marker shows your head position projected onto the display. The outer circle shows your approximate field of view. You will notice that the outer circle resizes itself when you walk towards/away from the display. This circle will keep the mouse cursor in a close proximity to your point of focus. That means, whenever you want to see where the cursor is on this big display, you only need to search inside this circle.

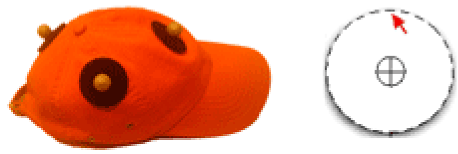

Figure 2., *the red trackable hat and gaze circles*

Navigation Techniques

For this experiment, you will use four navigation techniques

1. Gyro based navigation

In this technique you will use a gyration gyroscopic mouse, figure1, to zoom and pan on any points on the map. The technique is very similar to web map applications such as Google and Yahoo maps. You will use mouse wheel to zoom-in/zoom-out and mouse grabbing to pan to any direction on the map..

2. Gaze based navigation

In gaze based navigation technique, your position in the room will trigger panning and zooming action. That is you can no longer pan and zoom using the mouse. In order to zoom-in or zoom-out, you have to walk towards or away from the display, respectively. For panning, you will look at any point on the display boundary. The following figure shows how you zoom and pan using gaze based navigation technique.

Figure 3., *zooming and panning in gaze based navigation*

3. Absolute navigation

Absolute navigation is similar to gaze based navigation in that zooming operation works by physical movement. And this technique also requires you to look at display boundaries for panning operation. The only exception is that horizontal panning operation works only by physical movement, not your gaze. The following figure shows how you can zoom and pan using absolute navigation technique.

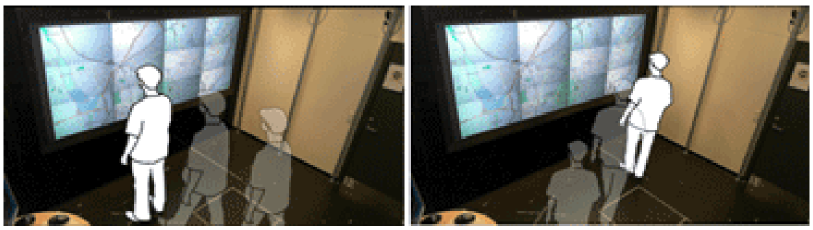

Figure 4., *zooming and panning in absolute navigation*

4. Relative navigation

In relative navigation, you will use the square region on the floor (hotzone) as your reference point to make zooming and panning. Standing still inside this region doesn't trigger any operation. In order to perform zoom-in or zoom-out you need to step out of the region towards or away from the display, respectively. The same technique applies to panning in the horizontal direction. When performing zooming or panning you will notice that the operation is continuous. If you want to stop current operation at certain zoom level or view you need to step back inside the hotzone. The following picture shows how you perform zooming and panning using relative navigation.

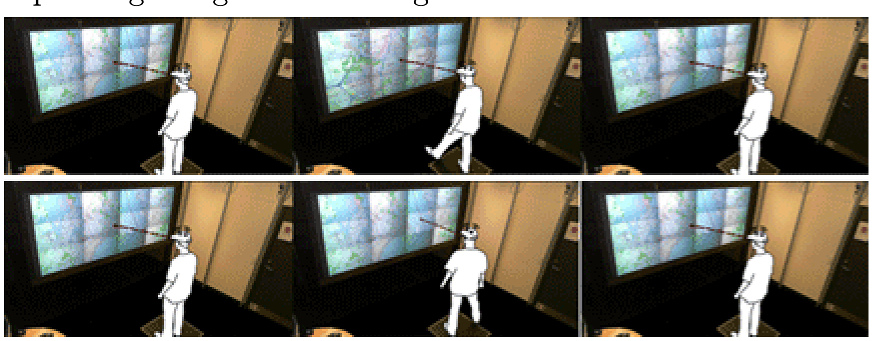

Figure 5., *zooming and panning in relative navigation*

For each navigation technique, you will be given four type of tasks

1. <u>Navigation</u>

In this task you will be given a single marker displayed on top of blue box at random point on the map. When you zoom-in and passes certain zoom level you will notice that the box color changes to green. The task here is to zoom-in to a target marker and click on it after the box turns to green. When it is done, you will see another target displayed at random point on the map.

2. <u>Search</u>

In search task, you will be given 10 targets displayed on top of blue box at any random point on the map. When you zoom-in and passes certain zoom level you will notice that the boxes color changes to red except four of the target markers. These markers will turn green after a certain zoom level. The task here is to find out one of these four markers and click at them. When it is done, you will see another targets at other part of the map. The following picture shows search task.

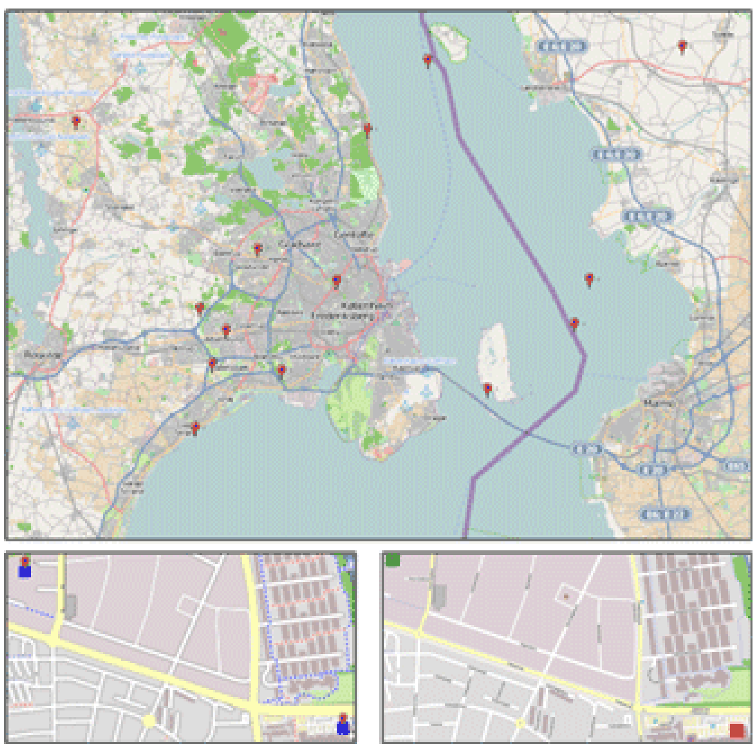

Figure 6, search task: (A) search target markers displaying 10 targets, (B-C) search targets before and after certain zoom level reaches, respectively. Green markers are targets, and red markers show false targets in search tasks.

3. Route tracing

In route tracing task, you will be given a sequence of markers displayed on close proximity to train/metro stations in Copenhagen area. The task here is to relocate these markers to the actual train/metro station location by dragging and dropping. The following picture shows route-tracing task.

Figure-7, route tracing task: targets are displayed on top of train station in Copenhagen area and are connected by straight lines.

After the completion of every tasks for each of the navigation techniques, you will be given a questionnaire to fill out your opinion about the navigation technique related to the task just completed. And after completing all tasks in all navigation techniques, you will be given another questionnaire to prioritize the navigation techniques.