To appear in Transactions of Geographical Information Science

INVESTIGATING HOLOGRAM-BASED ROUTE PLANNING

Sven Fuhrmann[1)], Oleg Komogortsev[2)] and Dan Tamir[2)]

1) Department of Geography, Texas State University, 601 University Drive, San Marcos, TX 78666, Email: fuhrmann@txstate.edu (corresponding author)

2) Department of Computer Science, Texas State University, 601 University Drive, San Marcos, TX 78666, Email: ok11@txstate.edu, dt19@txstate.edu

Short title: Hologram-based route planning

Keywords: Geospatial Holograms, 3D Geovisualization, Eye-Movement Analysis, Route Optimization, Spatial Thinking

INVESTIGATING HOLOGRAM-BASED ROUTE PLANNING

Abstract

It is often assumed that three-dimensional topographic maps provide more effective route planning, navigation, orientation, and way-finding results then traditional two-dimensional representations. The research reported here investigates whether three-dimensional spatial mappings provide better support for route planning than two-dimensional representations. In a set of experiments performed as part of this research, human subjects were randomly shown either a two-dimensional or three-dimensional hologram of San Francisco and were asked to plan a bicycling route between an origin and a destination point. In a second task, participants used these holograms to identify the highest elevation point in the displayed area. The eye-movements of the participants, throughout the process of looking at the geospatial holograms and executing the tasks, were recorded. The eye-tracking metrics analysis indicates with high statistical level of confidence that three-dimensional holographic maps enable more efficient route planning. In addition, the research group is developing a new algorithm to analyze the differences between participant-selected routes and a set of "good routes." The algorithm employs techniques used to represent the boundary of objects and methods for assessing the difference between objects in modern digital image recognition, image registration, and image alignment applications. The overall goal is to create a theoretical framework for investigating and quantifying route planning effectiveness.

1. Introduction

Spatial thinking is often a ubiquitous cognitive process that many humans do not explicitly realize or take for granted. In everyday activities we describe travel routes to out-of-town visitors, plan a trip to the supermarket, and search for a pleasant place to retire. Spatial thinking has been described as a collection of integrated cognitive skills. The Committee on the Support for Thinking Spatially (2006) refers to spatial thinking as a combination of three elements: 1) concepts of space, 2) tools of representation, and 3) processes of reasoning. The concepts of space and spatial reasoning allow humans to understand the environment around them, make decisions, and learn how to solve spatial problems. Spatial representations allow humans to store, represent, and retrieve spatial information. Spatial representations facilitate spatial learning and thinking and are essential for understanding, remembering, reasoning, and communicating spatial content and concepts.

Humans have numerous spatial representations at their disposal. Cognitive maps, physical two and three-dimensional maps, as well as recently introduced digital two and three-dimensional representations are just a few examples. Many three-dimensional, often interactive, representations e.g., Google Earth and Microsoft Virtual Earth, have been developed to support spatial thinking. Although there is no conclusive research on this topic; many researchers, developers, and users believe that three-dimensional representations provide superior usefulness and usability. The research reported here attempts to determine whether three-dimensional spatial representations support better spatial thinking then two-dimensional mappings. We specifically focus on route planning as one aspect of spatial thinking and investigate whether three-dimensional topographic maps enable more effective route planning compared to two-dimensional topographic maps. Our study uses geospatial holograms as three-dimensional representation media. Geospatial holograms provide almost the same physical properties and affordances as traditional maps. We created two geospatial holograms of downtown San Francisco: one that features a two-dimensional topographic representation of the area and a second hologram that displays the topography as realistic three-dimensional representation. These geospatial holograms enable direct comparison of two different visualization modes and allow focusing on route planning with two-dimensional vs. route planning with three-dimensional representations. Our overall hypothesis is that eye-movement analysis can be efficiently used to quantify route planning effectiveness and to compare route planning patterns. In an experimental setting we applied eye-movement recordings to investigate the visual cognitive processes of three-dimensional route planning.

In addition, our research involves the development of a new algorithm to analyze the differences between participant-selected routes and a set of "good routes" (i.e., routes selected by experts). The algorithm employs techniques used to represent the boundary of objects and methods for assessing the difference between objects in modern digital image recognition, image registration, and image alignment applications. Our prolonged goal is to create a theoretical framework for investigating the effectiveness of map-based route planning and additional map-based spatial thinking skills. The findings of the current research significantly advance the stated goal.

2. Geospatial Holograms

Since Dennis Gabor developed the first holograms in the late 1940s, holograms have been an object of scientific research and public interest (Heckman 1986; Stea 1976; Benton and Bove 2008; Hariharan 2002). Holograms are mostly known for visualizing three-dimensional objects for entertainment and eye-catching purposes in amusement parks and art exhibitions. Nevertheless, despite the fact that the technology is over half a century old and well documented, holography has not been incorporated with mainstream visualization technology. This is due to multiple reasons including the high degree of difficulty and long length of time for production. Additional reasons include high cost as well as inconvenient restrictions on features such as size, color representation, and viewing angles. With recent development of advanced holographic software and hardware, these limitations are starting to vanish (Benton and Bove 2008; Kasper and Feller 2001).

Holograms utilize the physics of light diffraction to create optical illusions of solid three-dimensional objects or scenes (Kasper and Feller 2001; Hariharan 2002). They use special photographic materials that can encode and reconstruct three-dimensional visual information by means of a diffraction or interference pattern that can recreate a light wave-front that would actually be reflected from a three-dimensional scene or object. The encoding of a light wave-front into interference patterns is a complex process beyond the scope of this paper. When correctly illuminated, holographic interference patterns are decoded by the human physiological system and a realistic three-dimensional scene appears before the human eye (Kasper and Feller 2001; Hariharan 2002; Heckman 1986).

One advantage of holograms is that users can view the representations without special glasses, goggles, or tethered eyewear. Only a single point light source, e.g., unobstructed sunlight, a standard LED flashlight, or a standard halogen light, is required to make the imagery visible (figure 1). Initially, input data for holograms were limited to physical objects that are on the same scale as the recording material. Nowadays, three-dimensional digital scanning technologies or existing digital three-dimensional models and scenes can be used to generate the input data for holograms. Furthermore, the holographic production process has mainly become digital and the production time for holograms has decreased from several days to several hours.

--- FIGURE 1 ABOUT HERE ---

In comparison to traditional maps and two-dimensional electronic displays, geospatial holograms have a low (1 mm) resolution on the surface, but offer extremely rich information content because of their directional resolution. Two-dimensional media, such as photographs or maps display the same information regardless of the viewing angle while geospatial holograms can display different spatial information according to the user viewing angle. Modern geospatial holograms can actually encode spatial information for over one million different viewing angles. In theory entirely different data sets (e.g., topographic maps) can be presented at different angles. Benton and Bove (2008) provide more information about latest holographic technologic developments.

Geospatial holograms are a unique category of holograms with special geovisualization requirements. The relatively low resolution of 1mm pixels (figure 2) requires (1) applying sophisticated generalizations to geospatial information, (2) generating sufficient text labels and general map elements, (3) avoiding strong height exaggerations that might cause blurred imaging, and (4) optimizing the monochromatic color scheme for geoinformation representation. “Geospatial holograms” can be defined as three-dimensional holographic spatial representations of natural or human-built environments. These geospatial holograms are generalized, symbolic depictions of an area and usually represent relationships and patters of geospatial objects and phenomena. Currently, most geospatial holograms are of monochromatic nature, but experimental true color geospatial holograms are available at a relatively high cost. The research project reported in this publication applies green monochromatic geospatial holograms. True color geospatial hologram design will be investigated in the future.

--- FIGURE 2 ABOUT HERE ---

3. Route planning

One important spatial thinking process is route planning, a daily mostly ubiquitously executed task. Route planning includes generating a possible path between an origin and a destination point. It is an initial part of the way-finding process that humans usually accomplish in familiar and unfamiliar terrain; using mental, analog, and digital spatial representations. Many spatial and non-spatial factors influence route determination. For example, bicyclist might chose a route with lower slope, but longer distance while a hiker might select the shortest distance without worrying about slope. Overall, route planning and route decision making involves subjective spatial thinking including cognitive mapping, as well as the use of objective external spatial representations.

As humans become spatially literate they develop spatial knowledge and cognitive processing abilities which enable succeeding in way-finding and other spatial problem solving processes. Downs and Stea (1973) identify the mental representation building process as cognitive mapping and the product as a cognitive map (Tolman 1948). The cognitive map is not a map-like, single scale, distortion-free representation (Tversky 1993; Kuipers 1983; Hirtle

1997). It is a personal mental representation of space that includes various media information (language, images, etc.) such as perspectives, reference points, and errors. (Tversky 2000, 1993; Kitchin and Freundschuh 2000).

Human spatial knowledge is assumed to consist of landmark knowledge, route knowledge, and survey knowledge (Blades 1991; Siegel and White 1975). Landmarks are spatial features that are used to locate oneself in the environment. They act as guides during way-finding (Blades 1991; Sorrows and Hirtle 1999). Route knowledge (procedural knowledge) enables following routes and describing sequences of landmarks (Siegel and White 1975; Cornell and Heth 2000). It is assumed that a sequence of decision factors (distances, turning points, etc.) is stored and supports getting from one place to another (Kuipers 1978; Thorndyke and Goldin 1980). Survey knowledge (also referred to as configurational knowledge) allows the understanding of spatial relationships (i.e., topology) in an environment (Siegel and White 1975; MacEachren 1991). Freundschuh (2000) contends that long exposure to an environment leads to survey knowledge and Thorndyke and Hayes-Roth (1980); Péruch et al. (2000) state that route and survey knowledge can be acquired directly from maps. Cognitive representations derived from maps, however, have been reported to be orientation-specific, while cognitive maps derived directly from environmental experience appear to be orientation-free (MacEachren 1992; Tlauka and Wilson 1996; Shepard and Hurwitz 1984). Billinghurst and Weghorst (1995), Péruch et al. (2000), Ruddle (2000) and Biocca (1997) report that cognitive mapping occurs while traveling through real environments and through the use of spatial products such as maps, photographs, verbal descriptions and virtual environments.

Cognitive mapping is the basis for way-finding, which allows reaching and recognizing a destination in a familiar or unfamiliar environment (Arthur and Passini 1992; Peponis et al. 1990). Downs and Stea (1977) describe the way-finding process in four steps:

- orientation: knowing, or understanding, location, and the spatial relations between current and target location.
- route planning: choosing a route that leads to the destination.
- route monitoring: monitoring the route taken to confirm that it is the correct route, going in the right direction.
- destination recognition: recognizing that the correct destination or a nearby point, has been reached.

Gärling et al. (1986) integrate these steps into an information processing model for human way-finding. They argue that, at the beginning of a way-finding situation, a destination is decided upon and localized using information obtained from the cognitive map and other media, e.g., a topographic map. Thereafter, the selection of a route to the destination takes place and the travel plan is executed. Changes in the travel plan might be necessary during execution, depending upon trip length, the complexity of the environment, and the familiarity of the subject with the environment. Upon arrival, the way-finding process is terminated (figure 3). This research does not address the full way-finding process. It focuses on the route planning process and evaluates the effectiveness of the process.

--- FIGURE 3 ABOUT HERE ---

4. Eye-Movement Analysis

4.1 Studies in Cartography and Geovisualization

Observing eye movements started in the early 19th century when scientists tried to scrutinize the types of information that the eyes absorb while moving (Dodge 1900). Later, eye movement recording developed into an important research method that is often employed in studies concerning understanding of reading patterns (Rayner 1998), usability studies (Poole and Ball 2004; Tamir et al. 2008), psychology (Field et al. 2004), and visual inspection (Vora et al. 2002).

Generally, humans direct their vision center, the fovea, towards objects and scenes they would like to observe. At a high level of abstraction, eye movements can be separated into saccades, (fast movements of the eye), fixations (a static and focused position of the eye), and pursuits (smooth following of a “slow” moving object) (Duchowski 2007). Detailed research connects eye movement patterns to various brain related activities including spatial memory and cognitive processes (Leigh and Zee 2006). Researchers assume that long fixation duration demonstrate high cognitive loads, great depth in cognitive processing, and sometimes, difficulty in problem solving (Castner and Eastman 1985; Duchowski 2007).

In the early 1970’s cartographers initiated investigations on the use of eye-movement analysis for understanding the visual cognitive processes of map reading and the impact of map complexity on that process (Steinke 1987; MacEachren 1995). The majority of the eye-movement studies in cartography were conducted in the 1970s and 1980s (Antes et al. 1985; Castner and Eastman 1984, 1985; Dobson 1977, 1979), yet only few studies were published in recent years (Heidmann and Johann 1997; Johann and Heidmann 1996; Bollmann, Johann, and

Heidmann 1999). Most cartographic eye-movement studies are concerned with questions about how maps might be read, and researchers are analyzing individual scan paths. These scan paths, however, are individualistic, especially if the study participants do not have a specific task to follow. Steinke (1987) describes these studies as "let see what happens when we place a map in front of somebody". Castner and Eastman (1984) conclude that map interpretation includes two factors: 1) graphic factors from the physical and Gestalt properties of mapping products, and 2) cognitive factors relating to the actual map interpretation activities. Instead of focusing on scan paths, Castner and Eastman (1984) suggest investigating the number of fixations, fixation durations, and inter-fixation distances. They conclude that researchers should ask how the eyes move and not where the subject looks. Unfortunately, eye-movement research declined in the mid 1980's a development that Steinke (1987) describes as: cartographers becoming doubtful and skeptic towards this kind of methodological approach. Recently, with emerging less-expensive eye-tracking hardware and software, new studies in eye movement recordings, specifically in geovisualization, are conducted and published (Swienty et al. 2008; Fabrikant et al. 2008).

4.2 Detection of Basic Eye Movement Types

Eye-movement observations can be processed to extract and analyze three basic eye-movement types: fixations, saccades, and pursuits. Fixations are eye-movements that keep an eye gaze stable with regards to a stationary target providing visual images with high visual acuity. Saccades are very rapid eye movements where the eye rapidly shifts from one fixation point to another fixation location. A pursuit stabilizes the retina to a moving object and follows the object smoothly. It is important to define the exact detection algorithm for eye-movement analysis, because different parameterizations of an algorithm might lead to different results (Komogortsev and Khan 2009). In the context of geospatial holograms the overall image properties are static, thus the pursuit movement observations can be ignored.

The detection algorithm applied in this research is based on the *Velocity-Threshold Identification* (I-VT) model (Salvucci and Goldberg 2000). A velocity-based classification approach has more synergy with oculomotor mechanics due to the fact that all eye rotations are measured in degrees rather than in a dwell time classification approach (Salvucci and Goldberg 2000). An eye position sample is classified as (1) belonging to a saccade if the calculated eye velocity exceeds 30°/s and (2) a fixation if the eye velocity is less than or equal to 30°/s. The threshold of 30°/s is justified by Leigh and Zee (2006). A saccade is defined as a sequence of continuous eye position samples with calculated velocity exceeding 30°/s. The saccade amplitude is defined as the Euclidean distance between the coordinates of the first and last point in that sequence. Saccades with amplitudes of less than 2° and saccades where the eye tracking failed to detect an eye position (even for a single sample) are discarded from analysis. A fixation is defined as a sequence of eye position samples with a velocity of less than 30°/s where the angular distance between samples does not exceed 2°. One parameter of interest is the fixation duration where in addition to actual fixation, sequences of eye tracking failures and blinks with less than 75ms are considered a part of the fixation duration. In our experiment, the minimum fixation duration is set to 100ms. A fixation location is defined as the average over all the valid eye-position coordinates, excluding micro saccades (saccades with amplitude of less than 1°). The eye fixation duration is defined as a time difference between the last and first samples in the fixation sequence.

Based on the algorithm applied, the following eye-tracking metrics are calculated for data analysis:

- Average saccade amplitude:
    - A large saccade amplitude (measured in degrees) indicates the “consumption” of meaningful visual cues (Goldberg and Kotval 1999). Therefore, large saccade amplitudes in geospatial representations might indicate effective representations.
- Average fixation duration:
    - Generally, long average fixation duration indicates a high cognitive load. Long average fixation durations can be interpreted in two different ways as either: 1) the user has difficulties extracting information or 2) the user is more engaged with interpreting a representation (Just and Carpenter 1976). Hence, distinguishing between the two is case specific.
- Number of saccades:
    - Generally, high number of saccades indicates that significant amount of searching takes place and therefore less time is allocated to efficient task completion (Goldberg and Kotval 1999).
- Number of fixations:
    - In general, a high number of fixations is indicative of a non efficient visual task. Many variables can influence the number of fixations, one of them could be poor representation designs (Goldberg and Kotval 1999).
- Saccade/fixation ratio:
    - This figure describes the ratio between search activity (represented by the number of the saccades) and processing activity (represented by the number of the

fixations). A small saccade/fixation ratio indicates that the user is spending more "cognitive resources" on the task (higher cognitive load) and less cognitive resources on gathering important background information (Goldberg and Kotval 1999). This particular metric is especially useful for eye movement recordings with low data validity rates.

- Pupil diameter:
  - Eye tracking systems enable measuring biometric data such as pupil diameter. There is evidence that suggests that pupil size increases when subjects are asked to process information. Likewise memory engagement, attention concentration, and comprehension of complex sentences might increase the pupil size (Andreassi 2006; Beatty 1982). Some researchers suggest that high pupil size might be indicative of a high cognitive load (Poole and Ball 2004).
- Total eye-path traversed:
  - The amount of effort expended by the Human Visual System (HVS) while completing a task is an important metric for the specific geospatial representation. Ideally, the effort expended by the HVS can be represented by the amount of energy spent by the HVS during the task. The energy expanded is dependent on the amount of eye movements, the total eye-path traversed, and the amount of force exerted by each individual extraocular muscle force during each eye rotation (Tamir et al. 2008). The extraction of the individual extraocular muscle force is an extremely complex task (Komogortsev and Jayarathna 2008). Therefore, in this manuscript we are using the total eye-path traversed as approximation for the

effort. This metric, measured in degrees, represents the total distance traversed by the eyes between consecutive fixation points during a task.

- Time on task
    - Time on task (TOT) is not an eye movement metric. Nevertheless, in this research the TOT is obtained from the eye tracking device by measuring the total time that the HVS is engaged with the task. TOT is another indicative of effort and effectiveness.

5. Effort Based Measurements of Usability

We are currently performing additional research were we establish relations between user interfaces, user effort, and usability. Usable applications require less user interaction effort in general. Thus, the current model estimates user mental and physical effort based on measurements of mouse, keyboard, and eye-movement activities. Geospatial holograms, and other geovisualization technologies, can be considered as user interfaces to geospatial and non-spatial information. Hence, we are in the process of transferring the effort-based usability model to our spatial thinking assessment framework.

Usability is a term that is broadly defined (Grady 1992; McCall et al. 1977; Nielsen 1993). The ISO/IEC 9126 standard defines usability as "the capability of a software product to be understood, learned, used, and attractive to the user when used under specified conditions" (Software Engineering-Product Quality-Part 1: Quality Model 2001), with the following characteristics: understandability, learnability, operability, attractiveness, and compliance. Another international standard, the ISO 9124, uses a slightly different denomination for usability; it lists efficiency, productivity, and satisfaction as the main factors of usability. This standard calls for evaluating the effort invested by the user as a part of the evaluation procedure, yet the actual definition of effort as well as ways to measure it, are not well defined. In practice researchers measure time on task and evaluate user activity; observations that might provide limited results for determining the mental effort and effectiveness of users working with geospatial holograms.

The premise of the research reported in (Tamir et al. 2008) is that there is a relationship between usability and effort. Let E denote the total effort, mental and physical, required to complete a task, as defined by the following equations:

$$E = \begin{pmatrix} E_{mental} \\ E_{physical} \end{pmatrix}$$

$$E_{mental} = \begin{pmatrix} E_{eye_{mental}} \\ E_{other\_mental} \end{pmatrix}$$

$$E_{physical} = \begin{pmatrix} E_{manual\_physical} \\ E_{eye\_physical} \\ E_{other\_physical} \end{pmatrix}$$

Most of the terms used in the equations are self explanatory and denote types of efforts required for task completion. On the other hand, E_{other_mental} and $E_{other\_physical}$ respectively denote the amount of mental and physical effort that cannot be represented through eye-tracking and other observation methods. They can be considered as an error term that accumulates the errors inherent in the logging and tracking along with the fact that there are other forms of mental and physical effort that is not be recorded.

Precise methods for measuring mental effort (E_{mental}) are still in a theoretical stage. Researchers have made progress measuring mental or cognitive activities using Magnetic

Resonance Imaging Systems. Another approach, still in the theoretical stage, is to measure cognitive activities using eye tracking analysis. Methods for estimating physical effort $E_{physical}$ are more precise. In the case of interface usability, it is possible to log subject's activities such as number of mouse clicks, number of keyboard clicks, and number of pixels traversed by the mouse thereby describing the manual effort ($E_{manual\_physical}$). Tracking eye movements with an eye tracking device provides a method for making a precise measurement of eye mental effort ($E_{eye_{Mental}}$) and eye physical effort ($E_{eye\_physical}$).

Lessons learned from this approach will be applied in future geovisualization research on effort-based measurements of usability and effectiveness, and provide a deeper insight into spatial thinking processes.

6. The experiment

6.1 Subjects

Thirty-eight undergraduate and graduate students from the departments of Geography, Psychology, and Computer Science volunteered for the experiment. Four students disqualified due to eye-tracking device failures. The remaining subject pool consists of 23 male and 11 female participants. The participant age ranges between 19-54 years with an average of 29.5 years (SD 9.6). Eight participants have no previous map interpretation experience, fourteen subjects describe their map interpretation skill level as moderate, and twelve participants consider themselves as experts in map interpretation.

6.2. Geospatial Holograms of San Francisco

A section of downtown San Francisco, CA serves as the study area for this research. Two monochromatic geospatial holograms with height of 590 millimeters and width of 833 millimeters represent a topographic map of that section (figure 4 and 5). Both geospatial holograms are at a scale of 1:5500, using 1mm holographic pixels and identical monochromatic color schemes. The difference between the two geospatial holograms, however, is that one hologram displays the elevation information in three-dimensions to the observer, while the second hologram is a “flat” two-dimensional hologram that does not convey elevation information directly. Like any other topographic map, the elevation information is encoded through contour lines in both geospatial holograms.

--- FIGURES 4 AND 5 ABOUT HERE ---

6.3 Procedure

Half of the qualified participants (17 out of 34) work with the two-dimensional hologram. The second half of the subjects utilizes the three-dimensional geospatial hologram. The hologram of San Francisco, covered behind a black curtain, is placed on a wall above a desk. The estimated distance between the subject’s eyes and the hologram is 1140 millimeters. Five markers, placed on the wall, are used to calibrate the eye-tracking device. A subject has to complete two tasks. The first assignment, task (1), is planning a bicycling route between an origin and a destination point using the hologram. No time limit is given for route planning. After planning the route, the subject draws the planned route on a paper map. The second assignment, task (2), consists of using the hologram to identify the highest elevation in the landscape. After identifying the highest point, the participant marks that point on a paper map.

Eye movement recordings are performed using a Tobii x120 eye-tracker with the following characteristics: sampling rate - 120Hz, accuracy 0.5°, spatial resolution 0.2°, and drift 0.3°. Tobii x120 eye-tracker is non invasive and allows for 30x22x30 cm freedom of head movement. Nevertheless to improve the accuracy of recording a chin rest is employed to fixate subjects head. Third party and own software is used to extract metrics from the recordings.

Each participant reports to the study individually, is briefed on the general scope of the study, is introduced to the workings of the eye-tracking device, and examines a hologram of a different urban area. Next, the participant is seated in a desk chair across from the covered hologram with his or her chins resting on a chin-rest. Once the eye tracking device is calibrated, the participant is ready to start the experiment. After lifting the curtain the subject's eye-movements and time to complete the task are recorded. Eye-tracking is stopped when the participant indicates that he or she finished the route planning task. The participant draws the selected route on a paper map and moves to the second task of identifying the highest elevation in the landscape. Again, the subject's eye-movements and time to complete the task are recorded until the participant indicates that he or she has identified the highest point. At this time, the participant marks the highest point on a paper map.

7. Results

The study includes two tasks: planning a bicycling route between two points (task1) and identifying the highest point in an area (task 2). It compares eye-tracking metrics of subjects executing the tasks while using a two-dimensional geospatial hologram with eye-tracking metrics related to the execution of the same tasks via a three-dimensional geospatial hologram (figure 6).

Micro saccades, i.e., saccades with amplitudes of less than 1°, are ignored. Furthermore, corrupted saccades, that is, saccades in which the eye tracking equipment fails for a part of the duration of a saccade are excluded. Data recordings with validity of less than 70% are removed from the metrics analysis. The results and conclusions presented here need to be considered as being preliminary, since additional studies are necessary to confirm these findings.

--- FIGURE 6 ABOUT HERE ---

The measurements of the average saccade amplitude (in degrees) with the three-dimensional geospatial hologram yield a mean of 4.32 with standard deviation of 1.17 ($M = 4.32$, $SD = 1.17$). The results of the average saccade amplitude with the two-dimensional geospatial hologram are ($M = 3.42$, $SD = 0.76$). The statistical significance of these results is: $F(1, 33) = 5.7$, with a level of confidence: $p = 0.02$. On average the saccade amplitude for the three-dimensional hologram is larger than for the two-dimensional hologram. These results indicate that three-dimensional hologram users might be able to efficiently move their eyes between distant points. The two-dimensional saccade amplitude results indicate that observers often move their eyes between closer located points. It seems that – based on saccade amplitude observations

– the three-dimensional geospatial hologram would support more efficient route planning than the two-dimensional counterpart.

The average fixation duration (in milliseconds) is (*M* = 485, *SD* = 173) with the three-dimensional hologram and (*M* = 753, *SD* = 697) with the two-dimensional hologram. In this case, $F(1, 33) = 3.11$, and $p = 0.087$. The longer fixation duration for the two-dimensional representation indicates that this representation might require a higher cognitive effort, possibly due to the less salient three-dimensional information embedded in two-dimensional spatial representations.

Another set of results is the ratio of the number of saccades to the number of fixations (the saccade/fixation ratio). The recorded ratio for the three-dimensional geospatial hologram (*M* = 0.88, *SD* = 0.31) is significantly lower than the ratio for the two-dimensional geospatial hologram (*M* = 1.21, *SD* = 0.2). The results significance is $F(1, 33) = 10.9$ and $p = 0.002$. These results indicate that, in general, three-dimensional hologram users might experience a smaller number of saccades and a larger number of fixations. It seems that users of three-dimensional holograms do not move their eyes as often as two-dimensional hologram users. This finding could be a good indicator for efficient route planning with three-dimensional geospatial holograms.

The average pupil diameter is larger for the three-dimensional geospatial hologram (*M* = 4.3, *SD* = 0.4) than for the two-dimensional geospatial hologram (*M* = 3.9, *SD* = 0.78). The difference between the results, however, is on the verge of statistical significance ($F(1, 33) = 3.87$, $p = 0.057$). This result might indicate that three-dimensional geospatial holograms provide more information to accomplish a route planning tasks, thus might require a higher cognitive processing load – a finding that needs to be further assessed.

The route planning task yields a higher time on task for the three-dimensional geospatial hologram ($M = 33$, $SD = 20.4$) than for the two-dimensional geospatial hologram ($M = 23.6$, $SD = 15$). The difference between these measurements is not statistically significant ($F(1,14) = 0.85$, $p = 0.317$).

The traversed eye-path for the route planning task is longer for the three-dimensional hologram ($M = 300$, $SD = 173$) than for the two-dimensional counterpart ($M = 158$, $SD = 69$). The difference in results for the traversed eye-path is also not statistically significant ($F(1,14)=3.08$, $p=0.101$). The latter two results might not necessarily indicate less effectiveness in route planning. In the case of the holographic representation and the novelty associated with it we can not rule out an “awe” effect. The results may also denote that a three-dimensional representation might contain more information to process and users might take the time to explore different routing options to find “their” best route – a finding that will further investigated.

8. Discussion

Eye-movement analysis allows to investigate one aspect about effective route planning with two and three-dimensional spatial representations. Steinke (1987) asserts that a combination of methods is required for understanding the cognitive processes in map interpretation. The eye-movement analysis sheds light on the effectiveness of three-dimensional spatial representations and indicates that three-dimensional maps might help performing efficient route planning. The eye-movement analysis, however, does not reveal information related to the quality of the planned route. In other words, it does not indicate whether users of the three-dimensional geospatial hologram plan better routes than users of the two-dimensional counterpart.

In order to investigate the initial findings of the eye-movement analysis we are developing a new algorithm that utilizes the image processing concepts and shape features to analyze the differences between participant-selected routes and a set of "good routes". In image processing, difference is measured using theoretical "distance" measures such as the Mahalonobis distance (Haralick and Shapiro 2002). Several image processing algorithms utilize shape features in the process of object matching and use distance between object contours for object matching (Brown 1992). This procedure can be utilized for identifying the distance (i.e., the difference) between routes. The following section explains the proposed "length code matching algorithm".

8.1 The Length Code Matching Algorithm

Object shape features such as chain codes, Fourier descriptors, and object-signature are often used for object matching and image registration (Freeman 1974; Haralick and Shapiro 2002). A desirable characteristic of many of these features is their set of invariants which can provide matching robustness. For instance, chain-codes are invariant to translation. A commonly used set of shape features is referred to as the object signature (Haralick and Shapiro 2002).

The term object-signature is "overloaded." In the context of this paper it is the set of distances measured from a fixed-point referred to as the 'center' (generally this point is centroid of the object) to pixels that reside on the object boundary (contour). In order to extract an object signature the image has to be segmented, objects have to be identified, and the pixels that reside on object contours have to be marked (Alajlan et al. 2006; Brown 1992). In our research, routes are drawn by participants on paper maps and manually digitized.

We propose using a variant of the object signature referred to as the "length code". The main advantage of the length code is that it is less sensitive to "noise". This is due to the fact that a small change in shape, which may be due to noise, causes minimal changes to the distance between the centroid and contour points. In addition, length coding is invariant to the entire set of affine transformations. Finally, this representation converts a two-dimensional problem into a one-dimensional problem without loss of information and provides a computationally efficient framework.

Generally, in image processing algorithms for object matching, the contours of objects are closed, i.e. the origin and the termination point are identical. The routes obtained in our eye-movement analysis experiment are generally "open" lines. They start in a point A and end in a distinct point B. Lines pose only a minor difference to the image processing algorithm, since an arbitrary reference point can be used.

The cyclic auto correlation function of the signature sequence is rotational and translational invariant (Baggs 1997; Haralick and Shapiro 2002). The first autocorrelation coefficient of the signature, R_0, is the sum of squares of the values of signature elements. Hence, it approximates the energy of the signal and is proportional to the area of the object. Thus, in order to normalize the sequence each autocorrelation coefficient R_i is divided by the coefficient R_0. The resultant sequence is scale invariant. It is referred to as the "length code" of an object. The length code is invariant with respect to translation, rotation, and scaling. Hence, it is invariant with respect to affine transformations.

An important contribution of the proposed algorithm is the usage of dynamic space warping (DSW), a dynamic programming (DP) algorithm, in the process of matching the length-code features of tours. In several pattern recognition applications, L1-norm, or L2-norm are used as the distance (or dissimilarity) measure. These measures work well under the assumption of linearity and for well-formed contours. When the patterns are subject to non-linear transformation and distortion due to different acquisition parameters, the L1 and L2 norms may fail to produce accurate results. This is actually the case for the routes designed by the subjects in the geospatial hologram tests. Each subject is drawing a route from a starting point to a destination point, and the set of routes can be considered as a non-linear transformation of the ideal route. A non-linear distance measure that can be considered in this case is the dynamic time (or space) warping function. In this research, the DSW algorithm returns a measure of the distance between two length-code sequences. The unique property of this distance measure is that it allows for spatial fluctuations in the object (routes in our case) representation and compensates for imperfections in digitization and shape representation.

Using experience obtained in object matching research (Baggs 1997; Baggs and Tamir 2008; Keogh et al. 2006), we are currently developing a DSW and length code based matching algorithm for the evaluation of routing quality. The algorithm and the findings of the research will be reported elsewhere.

9. Outlook

The international research agenda (MacEachren and Kraak 2001) of the Commission on Geovisualization, International Cartographic Association encourages scientists to further investigate the contexts within which geovisualization is successful. MacEachren and Kraak (2001) pillory repeated statements in geovisualization publications that provide common-knowledge claims about usefulness and usability of geovisualization without scientific proof.

The research presented here investigates the usefulness and usability of three-dimensional representations over two-dimensional spatial representations in route planning and way-finding situations. Route planning is a ubiquitous spatial thinking process. Evaluating this process requires sound theoretical foundations. For this end, we have developed a theoretical framework that is based on eye-movement analysis and measuring similarity between routes through a length code matching algorithm to analyze route planning outcomes. Overall, the eye-movement analysis provides important and promising results on route planning effectiveness with three-dimensional geospatial holograms. These results, however, should be further verified in consecutive studies.

The results from our length code matching algorithm, which will be implemented next, will provide additional findings on the context of successful geovisualization use. Our future research will extend this framework and investigate additional spatial thinking processes and different geovisualization technologies. In addition, it will investigate age related spatial thinking patterns. Steinke's (1987) last sentence on eye-movement analysis research in cartography is very euphoric: "let us move forward". We could not better summarize it and fully endorse this statement.

Acknowledgements

We would like to thank Roberto Campos, Tobii Technology AB and the thirty-four undergraduate and graduate students for their voluntary participation in the study. Zebra Imaging provided the geospatial holograms. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funding and participating agencies or companies.

Literature

Alajlan N. et al. 2006. *Shape Retrieval Using Triangle-Area Representation and Dynamic Space Warping*, Technical Report, University of Waterloo.

Andreassi, J. L. 2006. *Psychophysiology: Human Behavior and Physiological Response*: Lawrence Erlbaum Associates.

Antes, J. R., K.-T. Chang, and C. Mullis. 1985. The visual effect of map design: An eye-movement analysis. *The American Cartographer* 12 (2):143-155.

Arthur, P., and R. Passini. 1992. *Wayfinding - People, signs, and architecture*. New York: McGraw-Hill.

Baggs R. A. 1997. *Object Matching Using the Dynamic Programming Algorithm*, PhD, Dissertation, Florida Institute of Technology.

Baggs, R. A., and D. E. Tamir. 2008. "Image Registration Using Dynamic Space Warping", International Conference on Artificial Intelligence and Pattern Recognition, AIPR-08, Florida.

Beatty, J. 1982. Task-evoked pupillary responses, processing load, and the structure of processing resources. *Psychological Bulletin, 91*(2), 276-292.

Benton, S. A., and V. M. Bove. 2008. *Holographic Imaging*. New York: Wiley-Interscience.

Billinghurst, M., and S. Weghorst. 1995. The use of sketch maps to measure cognitive maps of virtual environments. Paper read at Proceedings of the Virtual Reality Annual Information Symposium, at Research Triangle Park, NC.

Biocca, F. 1997. The Cyborg's dilemma: Progressive embodiment in virtual environments. *Journal of Computer-Mediated Communication* 3 (2).

Blades, M. 1991. Wayfinding theory and research: The need for a new approach. In *Codnitive and linguistic aspects of geographic space*, edited by D. M. A. U. F. Mark. Dordrecht: Kluwer Academic Publishers, The Netherlands.

Bollmann, J., M. Johann, and F. Heidmann. 1999. *Kartographische Bildschirmkommunikation*. Edited by J. Bollmann. Vol. 13, *Beiträge zur kartographischen Informationsverarbeitung*. Trier: Selbstverlag der Geographischen Gesellschaft Trier.

Brown L. G. 1992. A survey of Image Registration Techniques, *ACM Computing Surveys*, ACM Press.

Castner, H. W., and J. R. Eastman. 1984. Eye-movement parameters and perceived map complexity - I. *The American Cartographer* 11 (2):107-117.

———. 1985. Eye-movement parameters and perceived map complexity. *The American Cartographer* 12 (1):29-40.

Committee on the Support for Thinking Spatially. 2006. *Learning to think spatially*. Washington, DC: The National Academies Press.

Cornell, E. H., and C. D. Heth. 2000. Route learning and wayfinding. In *Cognitive Mapping - Past, present and future*, edited by R. Kitchin and S. M. Freundschuh. London: Routledge.

Dobson, M. W. 1977. Eye Movement Parameters and Map Reading. *The American Cartographer* 4 (1):39 - 58.

———. 1979. The influence of map information on fixation localization. *The American Cartographer* 6 (1):51-65.

Dodge, R. 1900. Visual perceptions during eye movement. *Psychological Review* 7:454-465.

Downs, R. M., and D. Stea. 1977. *Maps in Minds - Reflecting on cognitive mapping*. New York: Harper & Row.

———, eds. 1973. *Image and environment*. Chicago: Aldine.

Duchowski, A. T. 2007. *Eye Tracking Methodology: Theory & Practice*. 2 ed. New York: Springer.

Fabrikant, S. I., Rebich-Hespanha, N. Andrienko, G. Andrienko, and D. R. Montello. 2008. Novel method to measure inference affordance in static small-multiple map displays representing dynamic processes. *The Cartographic Journal* 45 (3):201-215.

Field, M., K. Mogg, and B. P. Bradley. 2004. Eye movements to smoking-related cues: effects of nicotine deprivation. *Psychopharmacology* 173 (1):116-123.

Freeman H. 1974. Computer processing of line drawing images, Computer Surveys.

Freundschuh, S. M. 2000. Micro- and macro-scale environments. In *Cognitive Mapping - Past, present and future*, edited by R. Kitchin and S. M. Freundschuh. London: Routledge.

Gärling, T., A. Böök, and E. Lindberg. 1986. Spatial Orientation and Wayfinding in the designed environment - A conceptual analysis and some suggestions for postoccupancy evaluation. *J Arch Plan Res* 1986 (3):55-64.

Goldberg, J. H., and X. P. Kotval. 1999. Computer interface evaluation using eye movements: methods and constructs. *International Journal of Industrial Ergonomics, 24*(6), 631-645.

Grady, R. 1992. Practical Software Metrics for Project Management and Process Improvement: Prentice-Hall.

Haralick R. M. and G. Shapiro. 2002. *Computer and Robot Vision*, Vol. I and II, Addison Wesley.

Hariharan, P. 2002. *Basics of Holography*. Cambridge: Cambridge University Press.

Heckman, P. 1986. *The magic of holography*. New York: Atheneum.

Heidmann, F., and M. Johann. 1997. Modelling graphic presentation forms to support cognitive operations in screen maps. Paper read at International Cartographic Conference, at Stockholm, Schweden.

Hirtle, S. 1997. The cognitive atlas: Using GIS as a metaphor for memory. In *Spatial and temporal reasoning in geographic information systems*, edited by M. J. Egenhofer and R. G. Golledge. Oxford: Oxford University Press.

Johann, M., and F. Heidmann. 1996. ComTest - Kartographische testsoftware zur empirischen Untersuchung von Arbeitsprozessen am Bildschirm. Trier: Universität Trier - FB VI/Abt. Kartographie.

Just, M., A., and P. A. Carpenter. 1976. Eye fixations and cognitive processes. *Cognitive Psychology, 8*, 441-480.

Kasper, J. E., and S. A. Feller. 2001. *The complete hook of holograms - How they work and how to make them*. Mineola, NY: Dover Publications.

Keogh, E. et al. 2006. LB_Keogh Supports Exact Indexing of Shapes under Rotation Invariance with Arbitrary Representations and Distance Measures, *32nd International Conference on Very Large Data Bases*. Seoul, Korea.

Kitchin, R., and S. M. Freundschuh, eds. 2000. *Cognitive Mapping - Past, present and future*. London: Routledge.

Komogortsev, O. V., and U. K. S. Jayarathna. 2008. *2D Oculomotor Plant Mathematical Model for eye movement simulation.* Paper presented at the BioInformatics and BioEngineering, 2008.

Komogortsev, O. V., and J. I. Khan. 2009. Predictive Compression for Real Time Multimedia Communication Using Eye Movement Analysis. *ACM Transactions on Multimedia Computing, Communications and Applications Journal* 5 (1).

Kuipers, B. J. 1978. Modeling spatial knowledge. *Cognitive Science* 2 (2):129-154.

———. 1983. The cognitive map: Could it have been any other way? In *Spatial orientation - Theory, research, and application*, edited by H. L. Pick and L. P. Acredolo. New York: Plenum Press.

Leigh, R. J., and D. S. Zee. 2006. *The Neurology of Eye Movements*: Oxford University Press.

MacEachren, A. M. 1991. The role of maps in spatial knowledge acquisition. *The Cartographic Journal* 28 (Dezember 1991):151 - 162.

———. 1992. Learning Spatial Information from Maps: Can Orientation-Specificity Be Overcome? *Professional Geographer* 44 (4):431 - 443.

———. 1995. How Maps Work - Representation, Visualization, and Design. New York: The Guilford Press.

MacEachren, A. M., and M. J. Kraak. 2001. Research challenges in geovisualization. *Cartography and Geographic Information Science* 28(1): 1-11.

McCall, J. A., P. K. Richards, and G. F. Walters. 1977. Factors in Software Quality. : Nat'l Tech. Information Service.

Nielsen, J. 1993. *Usability Engineering*. San Francisco, CA, USA: Academic Press.

Peponis, J., C. Zimring, and Y. K. Choi. 1990. Finding the building in wayfinding. *Environment and Behavior* 22 (5):555-590.

Péruch, P., L. Belingard, and C. Thinus-Blanc. 2000. Transfer of spatial knowledge from virtual to real environments. In *Spatial Cognition II - Integrating abstract theories, empirical studies, formal methods, and practical applications*, edited by C. Freksa, C. Habel, W. Brauer and K. F. Wender. Berlin: Springer.

Poole, A., and L. J. Ball. 2004. Eye Tracking in Human-Computer Interaction and Usability Research: Current Status and Future Prospects. In *Encyclopedia of Human Computer Interaction*: Idea Group.

Rayner, K. 1998. Eye Movements in Reading and Information Processing: 20 Years of Research. *Psychological Bulletin* 124 (3):372-422.

Ruddle, R. A. 2000. Navigating overlapping virtual worlds: Arriving in one place and finding that you are somewhere else. In *Spatial Cognition II - Integrating abstract theories, empirical studies, formal methods, and practical applications*, edited by C. Freksa, C. Habel, W. Brauer and K. F. Wender. Berlin: Springer.

Salvucci, D. D., and J. H. Goldberg. 2000. Identifying fixations and saccades in eye tracking protocols. Paper read at Eye Tracking Research and Applications Symposium, at New York.

Shepard, R. N., and S. Hurwitz. 1984. Upward direction, mental rotation, and discrimination of left and right turns in maps. *Cognition* 18:161-193.

Siegel, A. W., and S. H. White. 1975. The development of spatial representations of large-scale environments. In *Advances in child development and behaviour*, edited by H. W. Reese. New York: Academic Press.

Software Engineering-Product Quality-Part 1: Quality Model. 2001. Geneva Switzerland: International Standards Organization.

Sorrows, M. E., and S. Hirtle. 1999. The nature of landmarks for real and electronic spaces. In *Spatial information theory - Cognitive and computational foundations of geographic information science*, edited by C. Freksa and D. M. Mark. Berlin: Springer.

Stea, D. 1976. Program notes on a spatial fugue. In *Environmental Knowing - Theories, Research, and Methods*, edited by G. T. Moore and R. G. Golledge. Stroudsburg, PA: Dowden, Hutchinson & Ross, Inc.

Steinke, T. R. 1987. Eyemovement studies in cartography and related fields. *Cartographica* 24 (2):40 -73.

Swienty, O., T. Reichenbacher, S. Reppermund, and J. Zihl. 2008. The role of relevance and cognition in attention-guiding geovisualization. *The Cartographic Journal* 45 (3):227-238.

Tamir, D., O. Komogortsev, and C. Mueller. 2008. *An Effort and Time Based Measure of Usability.* Paper presented at the 6th Workshop on Software Quality, 30th International Conference on Software Engineering.

Thorndyke, P. W., and S. E. Goldin. 1980. Spatial learning and reasoning skill. In *Spatial Orientation - Theory, Research, and Application*, edited by H. L. Pick and L. P. Acredolo. New York: Plenum Press.

Thorndyke, P. W., and B. Hayes-Roth. 1980. *Differences in spatial knowledge acquired from maps and navigation*. 1 ed. Santa Monica: The Rand Corporation.

Tlauka, M., and P. N. Wilson. 1996. Orientation-free representations from navigation through a computer-simulated environment. *Environment and Behavior* 28 (5):647-664.

Tolman, E. C. 1948. Cognitive maps in rats and men. *Psychological Review* 55:189-208.

Tversky, B. 1993. Cognitive maps, coginitve collages, and spatial mental models. Paper read at COSIT 1993, at Marciana Marina, Elba Island.

———. 2000. Levels and structure of spatial knowledge. In *Cognitive Mapping - Past, present and future*, edited by R. Kitchin and S. M. Freundschuh. London: Routledge.

Vora, J., S. Nair, A. K. Gramopadhye, A. T. Duchowski, B. J. Melloy, and B. Kanki. 2002. Using virtual reality technology for aircraft visual inspection training: presence and comparison studies. *Applied Ergonomics* 33:559-570.

List of Figures

Figure 1

Figure 2

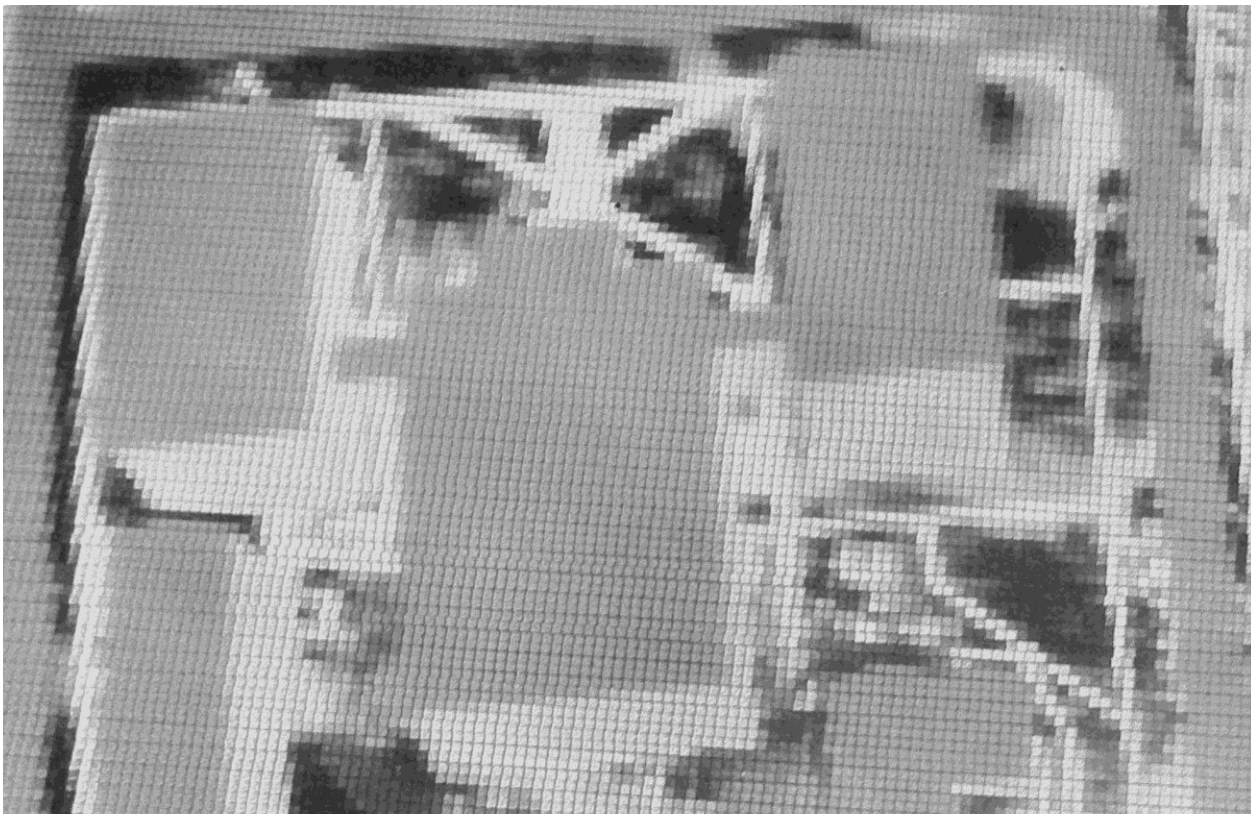
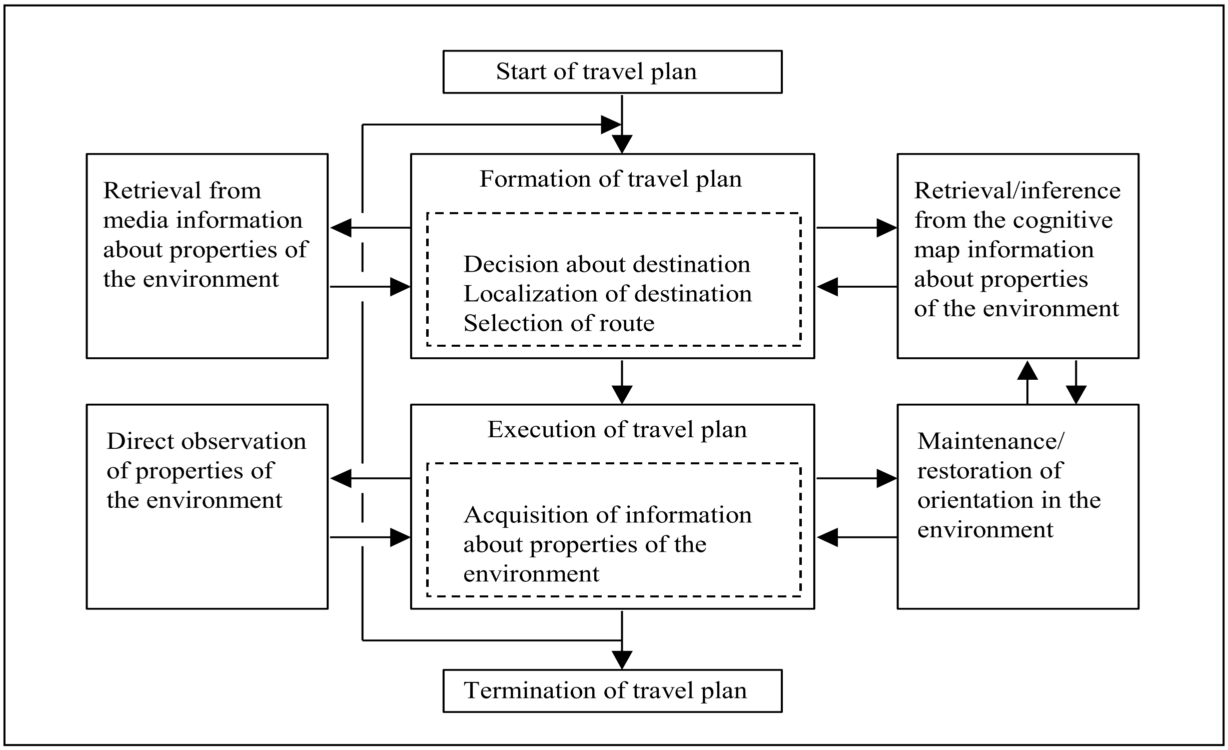


Figure 3



Start of travel plan
Formation of travel plan
Decision about destination
Localization of destination
Selection of route
Retrieval from media information about properties of the environment
Retrieval/inference from the cognitive map information about properties of the environment
Execution of travel plan
Acquisition of information about properties of the environment
Direct observation of properties of the environment
Maintenance/ restoration of orientation in the environment
Termination of travel plan

Figure 4

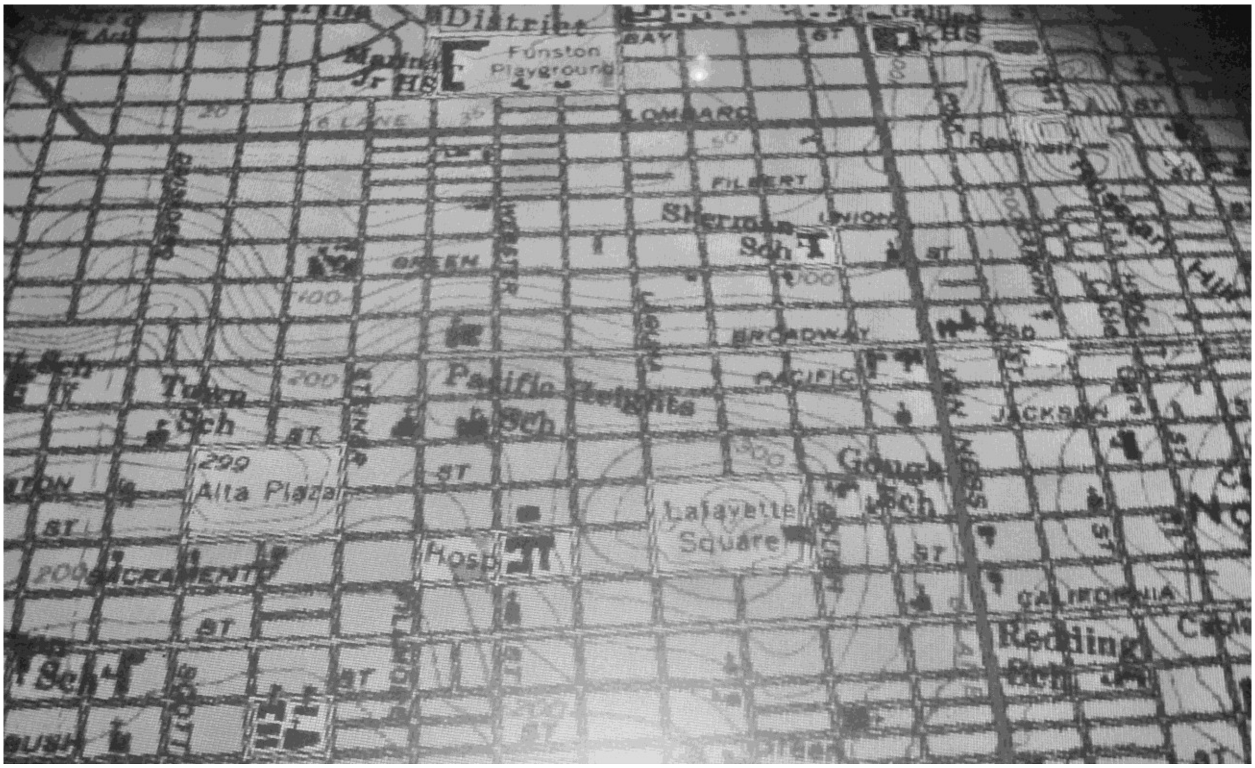
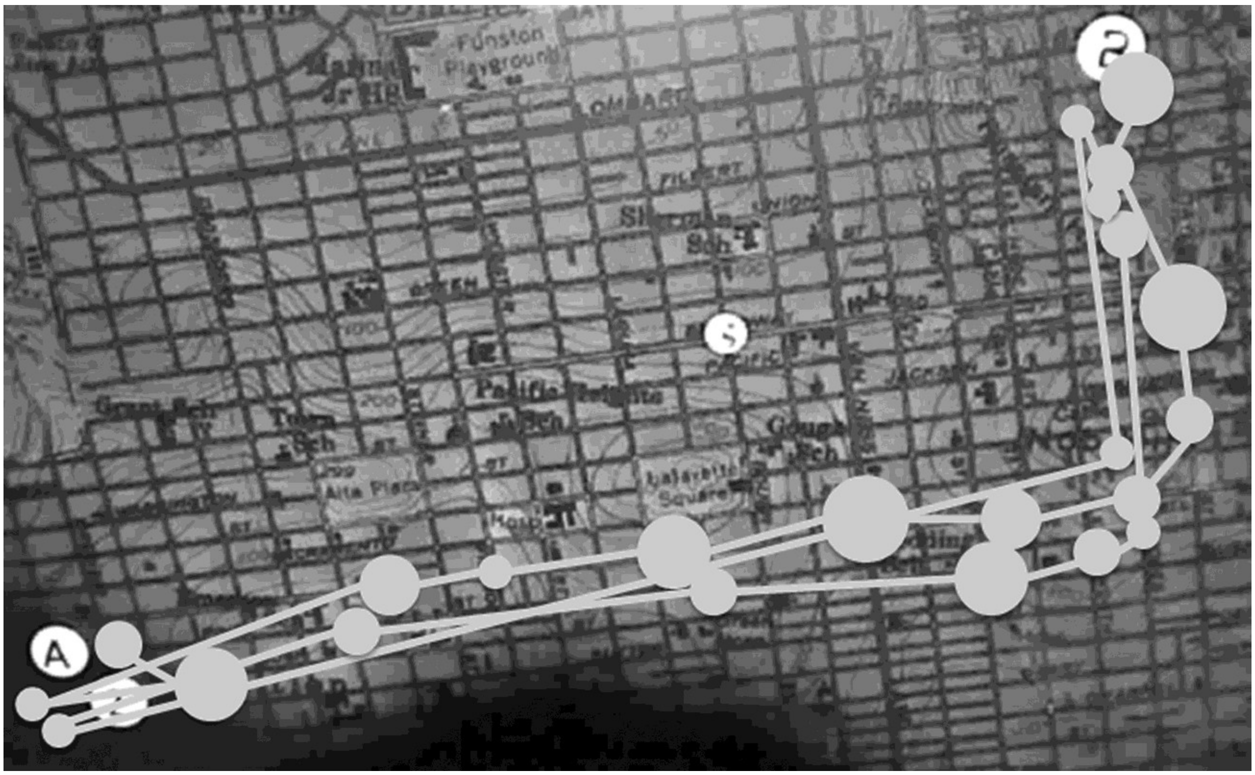

District
Funston Playground
LOMBARD
FILBERT
Sherman Sch
GREEN
BROADWAY
PACIFIC
JACKSON
299
Alta Plaza
Lafayette Square
Hosp
CALIFORNIA

Figure 5


District
Funston
Playground
LOMBARD
FILBERT
North Beach
Alta Plaza
CALIFORNIA

Figure 6



Funston Playground
LOMBARD
Pacific Heights
Alta Plaza
Lafayette Square
A