Rethinking the Mini-map: A Navigational Aid to Support Spatial Learning in Urban Game Environments

Numair Khan[a] and Anis Rahman[b]

[a]Computer Science Department, Brown University, Providence RI 02912; [b]School of Electrical Engineering and Computer Sciences, National University of Sciences and Technology (NUST), Pakistan

ABSTRACT

In urban game settings, players continue to rely on assistance for navigation even after hours of gameplay. This behavior is in contrast to the real world where spatial knowledge of an unfamiliar environment develops with experience, and reliance on navigational assistance declines. The slow development of spatial knowledge in virtual urban environments can be attributed to the use of turn-by-turn navigational aids. In the context of computer games, the most common form of these aids is a "mini-map" with route-highlighting. The use of such aids in computer games is necessitated by the demands of immersion and entertainment and, hence, they cannot be entirely discarded. The need, then, is to design navigational aids that support, rather than inhibit, the development of spatial knowledge. We propose *landmark-based* verbal directions as an alternative to mini-maps, and report the results of a randomized comparative study conducted to examine the impact of mini-maps and our proposed aid on the development of different levels of spatial knowledge in an open-world urban environment. The results confirm the superiority of our verbal aid at all three stages of spatial knowledge development. Mini-maps, however, perform better with respect to navigational efficiency. Based on the results of our study, we define design parameters that govern the tradeoff between navigational efficiency and spatial learning.

KEYWORDS

games; navigation; spatial; knowledge; cognitive; maps

1. Introduction

Recall the last time you moved to a new city. Buildings and streets were unfamiliar, requiring frequent recourse to navigational assistance. The layout of districts was unknown, inducing recurrent phases of disorientation. Nevertheless, as time passed and navigational experience in the new environment increased, routes and locations became more familiar. Very soon, travel between known locations was second nature. Not only that, but shortcuts and detours from commonly travelled routes could be made when necessary.

In our daily lives, such interactions with the environment are taken for granted. Shift attention to the increasingly complex virtual worlds of computer games, however, and the situation changes. Game players continue to rely on assistance for navigation, even after hours of gameplay. This disparity between the real world, and virtual worlds -

CONTACT Anis Rahman. Email: anis.rahman@seecs.edu.pk

which, in all other respects, ever more faithfully mimic reality - indicates a need to study how the latter are constructed, and how they are navigated.

In the real world, spatial knowledge is most commonly acquired through direct navigational experience. This process, however, can be time-consuming, particularly in virtual environments which lack the detail and, hence, the diversity of wayfinding cues that the real world offers. Hence, in the absence of veridical spatial knowledge, explicit navigational aids are used for orientation and route selection. In computer games, navigational aid usually takes the form of a miniature map, or a *mini-map*. Mini-maps come in a variety of forms. We restrict our attention in this study to concurrent (Darken and Peterson 2014) forward-up (Aretz and Wickens 1992) maps that provide information about all navigable routes in the local environment, as well as turn-by-turn navigational instructions through route-highlighting. Such mini-maps have become the *de-facto* standard for open-world urban settings, having been used in popular AAA game titles such as Saints Row, Watchdogs, and the Grand Theft Auto series. While supporting immediate wayfinding in unfamiliar environments, the use of navigational aids has been shown to impair the development of spatial knowledge in the long run (Gardony et al. 2013; Burnett and Lee 2005; Parush and Berman 2004; Parush, Ahuvia, and Erev 2007). Hence, the persisting inability of game players to navigate independently.

Despite their drawbacks, the use of navigational aids in computer games is necessitated by the demands of immersion and entertainment and, hence, they cannot be entirely discarded. Therefore, our research is concerned with finding alternate navigational aids that facilitate, rather than inhibit, the development of spatial knowledge in large virtual environments. The defining quality of any such navigational aid is that it *allows itself* to become redundant as navigational experience in the environment increases. This means that it provides navigational assistance in a manner as to develop long-term spatial knowledge, and, hence, enable creative wayfinding. This entails the development of spatial knowlege at the survey stage, that is, an understanding of the metrically scaled geographic relations between landmarks.

Our present work focuses on targeted navigational tasks in open-world urban environments in which a finite set of routes is clearly defined, and movement is restricted to these routes. Moreover, the player has complete autonomy in selecting a route between landmarks. As mentioned above, our goal is to study how survey knowledge development can be supported in such an environment using navigational aids. To this end, we propose the use of verbal navigational instructions that relate two landmarks in a geocentric frame of reference. Compared to mini-maps, not only are verbal instructions more natural, but we show that theories of cognitive psychology predict that verbal instructions, in the form we propose, support the development of spatial knowledge more effectively. (For convenience, the use of the term *verbal instructions* in the sequel assumes instructions of the particular form discussed above). A randomized comparative experiment was conducted to examine the impact of mini-maps and verbal instructions on the development of different levels of spatial knowledge in a virtual urban environment. Results show that compared to the mini-map group, participants in the verbal group were able to recall a greater number of landmarks, had better route knowledge, and navigated more efficiently in the absence of a navigational aid.

1.1. *Motivation*

Kevin Lynch, in his seminal work on citizens' perception of their city, described an *imageable* urban environment as one that "attracts the eye and ear to greater participation"(Lynch 1960). According to Lynch, spatial legibility was an important criterion for imageability. Alawadhi, Chandrasekera, and Yang (2014) link imageability to a sense of belonging, and show that it is positively correlated with spatial knowledge. Hence, spatial knowledge breeds familiarity, which in turns leads to the formation of an emotional bond with a place (Inalhan and Finch 2004). Since players will have a greater desire to revisit environments they have formed an emotional attachment to, spatial knowledge can lead to higher player retention rates.

Moreover, in the context of virtual environments, imageability may be compared to the concept of *presence* (Nash et al. 2000). Presence is described as the psychological state in which users stop being aware of the technology that is shaping their subjective experience (Tamborini and Skalski 2006). In other words, it is the feeling of being physically located in a virtual environment. Presence intensifies existing effects like enjoyment (Wirth et al. 2007) and, hence, can greatly enhance the entertainment value of media such as open-world computer games.

1.2. *Novel contribution*

The original contribution of this study is as follows:

(1) Propose a landmark-based verbal navigational aid that facilitates the development of survey knowledge in open-world computer games.
(2) Present and analyze the results of a randomized comparative experiment conducted to examine how our proposed navigational aid compares to a mini-map in terms of spatial knowledge development. Tha aids were used for targeted navigational tasks in a virtual urban environment .
(3) Explore design parameters that would allow the development of new navigational aids that support spatial learning.
(4) Provide a mapping from the space of design goals to navigational aids.

1.3. *Organization*

The remainder of the paper is organized as follows: The next section provides an overview of existing work on the subject. Influential frameworks of spatial knowledge development are revisited, along with several studies exploring the effects of navigational aid on spatial learning. The use of maps as a particular form of navigational aid is considered in light of theories from cognitive psychology. The section after that examines the theoretical arguments against mini-maps and presents the details of our proposed navigational aid. The following section discusses the experimental setup and our methodology. The 3D urban environment created for the purpose of our experiment is described. This is followed by the presentation and discussion of results. A concluding section summarizes our main findings.

2. Related work

2.1. *Development of Spatial Knowledge*

Siegel and White's three-stage model – arguably the most influential framework of spatial cognitive microgenesis – posits a knowledge development sequence comprised of three distinct phases (Siegel and White 1975). Landmark knowledge acquisition in the initial stage is followed by the ordering of learnt landmarks, and the paired association of egocentric spatial decisions with particular landmarks to yield route knowledge. Individual routes are then metrically scaled and integrated in a common allocentric frame of reference. The resulting configurational representation, called survey knowledge, is considered the most sophisticated form of spatial knowledge, supporting creative wayfinding.

While subsequent research has debated the order in which the stages occur (Garling et al. 1981; Garling, Book, and Ergezen 1982), insofar as the trichotomic division of spatial knowledge development is concerned, these studies agree with Siegel and White. Criticism of the three-stage model comes from Montello (1998) who argues for an alternate framework which postulates continuous quantitative accumulation of metric spatial knowledge rather than discrete qualitative shifts from non-metric to metric forms of knowledge. Ishikawa and Montello (2006) qualify Montello's framework by suggesting that significant qualitative and quantitative variations in the development of spatial knowledge may exist at the individual level. Blades (1991), and Yeap and Jefferies (1999, 2000) echo Montello's criticism of Siegel and White's framework. Yeap and Jefferies present a model of cognitive development which begins with representing the extent of the local space. Landmarks and other objects in the environment are then described using a local coordinate system. According to Moore (1976, 1972) underlying the structure of any representation of large-scale space is a system of reference which provides a framework for images of specific elements. Based on the earlier work of Piaget, Moore posits three main types of reference systems and suggests a sequential development from the first system to the third: an undifferentiated egocentric frame of reference develops, through an intermediate stage of partially-coordinated clusters of environmental elements, into a fully-coordinated global reference system. The representations suggested by Moore's frames of reference correspond only roughly with Siegel and White's stages of spatial knowledge. The very first stage in Moore's taxonomy suggests a spatial representation closer to rudimentary route knowledge than landmark knowledge. This view is supported by MacEachren (1992) and, implicitly, by Moore himself who states that allocentric systems of reference do not develop until some topological, projective, and Euclidean relations have already been established between environmental elements (Moore 1972). Moreover, while the partially coordinated reference system of Moore's second stage subsumes advanced route knowledge, it also implies more than a simple chaining of landmarks, and is more accurately characterized by the *anchor-point* framework described by Couclelis et al. (1987) and by the *complexes* of Lynch (1960).

Research on the acquisition of spatial knowledge commonly differentiates between route and survey descriptions as two methods of learning a new environment (Golledge, Dougherty, and Bell 1995; Golledge 1999; Thorndyke and Hayes-Roth 1982; Werner et al. 1997). No definitive statement can be made, however, as to which description is superior (Thorndyke and Hayes-Roth 1982; Taylor and Tversky 1992)

In brief, two common features of the above-mentioned developmental frameworks are the foundational role of landmarks, and the recognition of survey knowledge as the most sophisticated representation of macro-spatial knowledge.

2.2. *Effect of Navigational Aids on Spatial Memory*

Aslan et al. (2006) and Münzer et al. (2006) found that both route and survey knowledge developed more accurately in subjects who memorized directions before travel as compared to those who relied on mobile navigational aids during travel. Münzer et al. attribute this advantage to the greater mental effort invested by the former group in retaining the learnt directions in working memory. However, this interpretation only accounts for the group's superior route knowledge. It does not explain why the same subjects are more effective at integrating individual routes from memory into a coherent survey representation. In fact, as both experiments measured subjects' survey knowledge by making them indicate the position of landmarks on existing route maps, it is possible the subjects' route knowledge acted as a confounding variable. A more widely used measure of survey knowledge is a sketch-map drawn on a blank piece of paper. Burnett and Lee (2005) observed that sketch-maps were less accurate in the case of subjects guided by a vehicle navigation systems as compared to those who used a physical map or written instructions. In addition to citing depth of mental processing as a possible cause, the authors impute decreased attention to landmarks, less exposure to the environment, and a lack of navigational stress. Parush, Ahuvia, and Erev (2007), testing judgment of relative direction (JRD) – another widely used measure of spatial knowledge – conclude that automated navigation degrades the acquisition and transfer of spatial knowledge by lowering the requirement of mental effort during learning. This explanation is based on the levels-of-processing framework of Craik and Lockhart (1972) which states that persistence of memory traces is determined by the extent to which a stimulus is analyzed. As actively making route-decisions is likely to involve deeper cognitive analysis than passively following route directions, the same framework can be used to interpret the results of Bakdash, Linkenauger, and Proffitt (2008), who found that independent navigational decision-making is a significant factor in retention of spatial knowledge as measured by both sketch-maps and judgments of relative direction. Hence, any form of navigational assistance that relieves the user of the responsibility of decision-making is likely to impair spatial memory. Fenech, Drews, and Bakdash (2010) share a similar view. The work of Gardony et al. (2013) seems to indicate that decision-making is only marginally important to spatial memory encoding, but the authors concede their findings are not conclusive.

The inattention to landmarks, observed by Burnett and Lee, in subjects provided with navigational aids may, in fact, be another manifestation of the lack of mental investment during the learning process. Gardony et al. (2013), and Ishikawa and Takahashi (2013) confirm that treatments provided with navigational aids are likely to remember fewer landmarks that those without. Given the foundational role of landmarks in the development of spatial knowledge, this trend may be a significant factor in the deleterious effect of aids on spatial memory (Burnett and Lee 2005).

2.3. *Maps as Navigational Aids*

The analysis of all but one of the above-mentioned studies is restricted to navigational aids consisting of verbal, egocentric turn-by-turn instructions. Nonetheless, based on Craik and Lockhart's framework (Craik and Lockhart 1972), we may assume that the results generalize to any aid that reduces the mental effort invested by the subject, or removes the burden of navigational decision making from the subject. Hence, maps, as navigational aids, can be expected to have a similar effect on spatial knowledge acquisition. In fact, for visual navigational aids such as maps, cognitive psychology provides even further theoretical evidence of interference with spatial learning. Baddeley and Hitch (1974); Baddeley (1992) propose a model of working memory composed of three subsystems: the central executive, the phonological loop, and the visuo-spatial sketchpad. The visuo-spatial sketchpad is responsible for storing and manipulating visual, as well as spatial information. Since the processing of these two kinds of information is not functionally distinct, spatial memory is impaired by a concurrent visual task (Beech 1984). While subsequent research has shown that interference between a visual and spatial task is not as strong as interference between two spatial or two visual tasks, some form of interference does, nevertheless, occur (Klauer and Zhao 2004).

Darken and Peterson (2014) further point out that, with maps, a transformation from the egocentric to the geocentric perspective is required in order to locate the ego on the map. This operation places additional load on cognitive resources. Aretz and Wickens (1992) break the transformation down into two mental rotations: one, to bring the map into an upright alignment, and the other to align the map with the forward view of the ego. Electronic map displays in games and vehicle navigation systems attempt to relieve the cognitive load of performing these operations by indicating the ego's position on the map with a marker, and rotating the map to always maintain a *forward-up* orientation. While this makes the immediate task of locating the ego on the map simpler, it impairs spatial knowledge in the long run as the different perspectives from which the constantly re-orienting map is viewed need to be integrated into a coherent whole. Wiener, Meilinger, and Berthoz (2008) show that these additional spatial transformations lead to an increased error rate in spatial judgments. Hence, the decision to use forward-up maps represents an instance of the tradeoff between navigational efficiency and spatial knowledge that all navigational aids make.

Darken and Sibert (1993) present a set of navigational aids, derived from real-world analogs, to assist with search tasks in virtual environments. Subsequent studies by the same authors (Darken and Sibert 1996a,b), and Darken and Peterson (2014) analyze the effect of these mediators on spatial knowledge acquisition in a virtual environment. The former study found that treatments shown on-screen maps during navigation drew more accurate sketch-maps than treatments not provided any navigational aid. It should be noted, however, that the trial environment in this study consisted of a sparse open sea world, without routes or distinguishable landmarks. Most practical environments can be expected to contain landmarks and routes for subjects to base their spatial knowledge on, and to use as *implicit* wayfinding aid. The absence of explicit aid should not be construed as the absence of all wayfinding aid.

Streeter, Vitello, and Wonsiewicz (1985) found that pre-recorded vocal instructions lead to more efficient navigation than using a paper route-map with the desired route highlighted. However, the authors did not compare the two treatments for spatial knowledge of the trial environment. One may also question whether the results of the experiment, which used paper maps, extend to dynamically updating electronic maps.

2.4. *Methodologies*

A parenthetical note on the methodologies used to measure spatial knowledge is in order here. Even though widely used in research, sketch-mapping as a measure of spatial memory has been questioned by critics who point out subjectivity of assessment, the drawing and cartographic capability of subjects, and size of paper as possible confounding factors (Blades 1990; Kitchin 2000). In addition, maps force an Euclidean metric on pairwise cognitive distance estimates when no such metric necessarily exists (Montello 1991); in cognitive representations of space, the distance from point A to B is not always equal to the distance from B to A. Conversely, Billinghurst and Weghorst (1995) empirically demonstrate that sketch-maps accurately reflect topological, if not metric, spatial knowledge. They do not, however, directly address the aforesaid points of criticism.

Nor is the charge of bias unique to sketch-mapping. In a study comparing thirteen different tests designed to measure spatial knowledge, Kitchin (1996) found that the performance of subjects was inconsistent across tests, hence, indicating that methodological biases were present in each test. To overcome these inherent biases, Kitchin advocates research designs that use multiple, mutually supportive tests. Montello (1991) provides a review of methodologies for measuring cognitive distance, and discusses their relative advantages and disadvantages. However, while neither Kitchin nor Montello explicitly make the distinction, their work concentrates on measuring only the survey level of spatial knowledge.

3. A New Navigational Aid

From the discussion in the preceding section, the following factors may explain why mini-maps inhibit the development of spatial knowledge in virtual environments:

(1) *Increased cognitive load.* When *concurrently* used with navigation, *unmoded* mini-maps (Darken and Peterson 2014) add to the visual load on the visuo-spatial component of working memory, thereby, limiting the capacity for spatial processing. This is especially true if the map is not *forward-up* (Aretz and Wickens 1992), since then the user needs to perform a mental rotation of the map, in addition to processing two different visual representations of the world.

While one may argue that the visual load can be reduced by focusing all attention only on the mini-map, in most cases, doing so is not possible. The mini-map does not provide information about obstacles in the immediate environment, such as cars and pedestrians. Hence, to avoid these, both the world and the mini-map must be processed simultaneously.

(2) *Poor landmark recall.* Users of navigational aids have poor memory of landmarks (Burnett and Lee 2005; Ishikawa and Takahashi 2013). Since landmarks act as foundational elements of spatial knowledge, poor recall of landmarks directly affects spatial microgenesis.

The inability to recall landmarks may be due to lack of attention resulting from increased cognitive load on the visual component of working memory, as discussed above, or it may stem from shallow processing of stimuli (Craik and Lockhart 1972). In addition, studies on attention modeling have revealed that human gaze fixation tends to be biased towards the center of static or moving images (Tseng et al. 2009). Hence, landmarks are unlikely to attract attention unless they fall within this natural locus of attention, or, alternatively, unless top-down stimuli move visual attention to peripheral regions of the image (Borji and Itti 2013).

(3) *Lack of spatial decision-making.* By automating route-planning, turn-by-turn navigational instructions - as the class of mini-maps we consider indeed are -

relieve users of the responsibility of spatial decision-making . As this reduces the mental effort expounded during navigation, by Craik and Lochkart's framework (Craik and Lockhart 1972), memory of the environment is impaired.

In short, the drawbacks of mini-maps can be put down to the kind of environmental information presented, the manner in which it is presented, and the modality in which it is presented. In light of these factors we propose an alternate navigational aid based on geocentric landmark-based verbal directions. Verbal information is unlikely to interfere with the visuo-spatial working memory (although, as De Beni et al. (2005) suggest, the spatial component of working memory may be selectively involved in processing texts with spatial information). In addition, the dual-coding theory of learning predicts improved performance on knowledge transfer problems when visual and verbal information is presented together (Mayer and Sims 1994).

The verbal directions specify a *destination*, and state its position, in a geocentric frame of reference, with respect to a *source*. Relating landmarks in a geocentric frame of reference reinforces the allocentric representations of space in addition to the egocentric ones updated by locomotion through the environment (Mou et al. 2006). Hence, an example of directions in this format would read, "Proceed to *the Park* located to the south of *the Cathedral*," where both *the Park* and *the Cathedral* are visually salient landmarks in the environment.

The task of finding both landmarks is left to the user, although, in the interest of navigational efficiency, the source should be a landmark already in view of the user. A search task forces the user to invest mental effort in the environment leading to more persistent memory traces (Craik and Lockhart 1972). Specifying the direction of the destination with respect to the source helps limit the search area; again, an important consideration with respect to navigational efficiency. In addition to persistent memory traces, the requirement that users perform a visual search provides a top-down stimulus to visual attention, and helps overcome the center-bias of gaze fixation (Tseng et al. 2009).

4. Method

This section describes the details of an experiment conducted to compare the proposed navigational aid with mini-maps in terms of the effect of each on spatial knowledge development in a real-time virtual environment. For the remainder of the discussion, a distinction is made between the participant, and the participant's *avatar* in the virtual environment.

4.1. *Design*

The experiment was designed as a blind randomized comparative experiment with two groups: the first group was presented with a mini-map (henceforth, the *mini-map group*), whereas the second group received verbal navigational instructions in the format proposed above (the *verbal group*). These two navigational aids constitute the independent variables of our experiment. A navigational aid subsumes both the kind of environmental information presented to the user, and the modality (visual/verbal) in which it is presented. The participants' spatial knowledge was the dependent variable.

4.2. *Testing Environment*

Navigational tasks were performed in a virtual world consisting of a 750×1050 meters urban environment - henceforth, *the city* - created specifically for the purpose of the experiment (Figure 1a). The 3D model of the city was created using the Esri CityEngine software which allows procedural generation of urban environments from a set of user-defined production rules (Müller et al. 2006; Parish and Müller 2001). The benefits of procedural modeling in the current context are twofold. First, procedural models exhibit far greater variety of content than human-generated models, ensuring each *view* in the environment, as defined by Tverksy (2000), is unique. Second, the visual characteristics of the environment are made explicit and, hence, open to analysis, in the set of production rules.

The urban environment consisted of thirty three blocks and almost 150 unique buildings, of which 31 were designated landmarks. Landmark buildings were modelled as commercial or business units as we believe doing so made the landmark both visually and symbolically salient in the given setting (Figure 2). A sign prominently displayed the name of the landmark. All but three of the landmarks were positioned at street junctions - the three exceptions being made to allow the investigation of the effect of landmark position on navigational efficiency with our verbal wayfinding instructions. Following Vinson's (Vinson 1999) design guidelines, props were placed around landmarks to increase the distinctiveness of the latter. These props included billboards, water tanks, bus stops, phone booths, newspaper boxes, mailboxes, and traffic and street lights. There was only a finite set of navigable routes in the environment. These corresponded to the streets of the virtual city, and none of them ended in a cul-de-sac.

The final interactive environment was created using the Unity game engine.

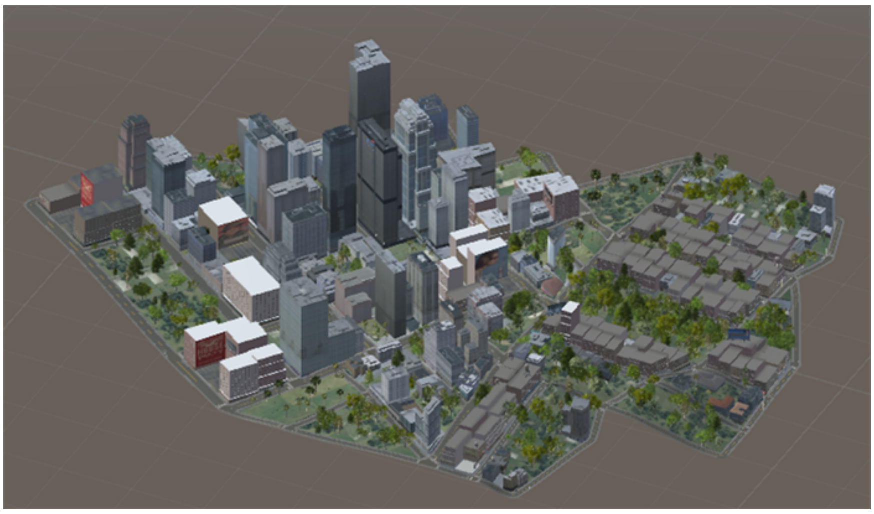
4.3. *Experimental Tasks*

The experiment was divided into a learning phase, a pre-trial testing phase, and a trial phase.

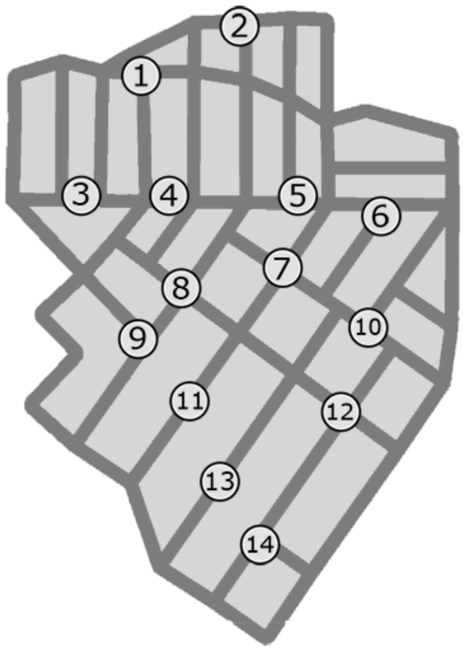
In the **learning phase**, participants were asked to use their assigned navigational aid to follow a route defined by a sequence of landmarks. We shall refer to this sequence as *the itinerary* to differentiate it from general routes. The distance between two consecutive landmarks on the itinerary shall be referred to as the *source-destination distance.*

In the **pre-trial testing phase**, participants were asked to complete a set of three tests, each designed to measure a separate stage in Siegel and White's model of spatial microgenesis (Siegel and White 1975). These tests were administered before the trial so as to not confound their results with any new spatial learning that may occur during the trial phase. The tests were:

(1) *Map Drawing.* This test required participants to draw a sketch map of the virtual environment. It provides a measure of survey knowledge.
(2) *Topological Ordering of Landmarks.* Participants were presented with a route map of the city on which the position of landmarks had been indicated by small numbered circles. The participants' task was to list the landmark corresponding to each numbered position. Where several landmarks were present in close proximity, a single numbered circle was drawn and a response listing any of the proximal landmarks was considered correct. The output of this test was an ordered list of landmarks. By providing all relevant metric information, this test



(a)



(b)

Figure 1.: **Testing Environment:** (a) shows the 3D urban environment created for the purpose of the experiment. (b) provides a survey view of the 3D environment with the position of landmarks indicated by the small circles.

Figure 2.: **Landmarks:** A landmark modelled as a commercial building. Also seen in this image are props around the landmark, meant to increase the distinctiveness of the latter.

requires only an understanding of the topological layout of landmarks - hence, the name chosen for the test. Such a non-metric understanding of landmark layout corresponds with rudimentary route knowledge.

(3) *Landmark recall.* Images of a three-dimensional urban environment were shown to the participants who were asked to decide whether or not they recalled seeing that particular scene during the learning phase. A small proportion of the images shown was not of the experimental environment. The number of correct responses, along with the number of false positives and false negatives was recorded. This tests memory for individual landmarks without any metric or non-metric association to other landmarks, thereby, providing a measure of the landmark stage of spatial knowledge development.

In addition to measuring different stages of spatial knowledge, the three tests were motivated by the need to have multiple mutually supportive measures to overcome biases inherent in each individual measure (Kitchin 1996).

The **trial phase** was designed to provide a practical measure of the survey knowledge acquired by each group. The participants were again required to navigate an itinerary in the game world. However, in this case, they were required to do so without the support of any navigational aid. Presenting a subset of landmarks from the learning phase in a different order ensured that the trial phase did indeed measure survey, and not route, knowledge. The navigational efficiency, as measured by the average distance travelled per landmark, was used as a metric of spatial knowledge.

4.4. *Navigational Aids*

The goal of each navigational aid was to assist participants in finding a route to some target location, which we shall call *the destination*.

4.4.1. Mini-map

The mini-map was a forward-up (Aretz and Wickens 1992), concurrently used and unmoded (Darken and Peterson 2014) route map of the city with the position of the participants' virtual avatar marked by a small triangle (Figure 3a). The map was displayed in the upper right corner of the screen. It showed every single navigable route in the local environment, with the route originating from the position of the avatar to the destination highlighted in bright green and updated in real-time. Thus, the mini-map provides turn-by-turn route directions. The selection of a route was done automatically using the greedy best-first search algorithm on a graph representation of the street network.

It should be noted that the mini-map was a replica of the *de-facto* standard navigational aid used in urban open-world games by the game industry. As such, the position of landmarks (in the sense of visually salient features of the environment) was not embedded on the map, nor was any geocentric directional information provided.

4.4.2. Verbal Instructions

The verbal aid provided participants with textual navigation instructions relating, in a global frame of reference, the destination, and a landmark close to the avatar. Thus, instructions were of the general form,

> "There is a *[destination]* roughly to the *[direction]* of the *[source]*. Go there."

For the current experiment, *[direction]* was chosen to be either one of the cardinal or intercardinal directions, and *[source]* referred to the last landmark visited on the itinerary. A compass positioned at the top center of the screen showed the avatar's current heading in terms of the cardinal directions. Figure 3b shows the interface for the verbal aid.

The cardinal and intercardinal directions mentioned in the verbal instructions provided only an estimate of the destination's location, and a beeline route to the destination in said direction was not always available. Hence, participants were often required to perform a local search of the environment to reach the destination. In case participants wandered too far off target, a message informing them of this circumstance was displayed. The message remained on screen until the participant's avatar was back within a threshold radius of the destination.

Comparing the two navigational aids in terms of the information provided, we may say that the mini-maps, by presenting a relative ordering of landmarks and enforcing the paired association of egocentric spatial decisions with landmarks along a route, provide complete route information. The information provided by verbal instruction, on the other hand, may be said to lie somewhere between route and survey information. While they do relate landmarks in a common allocentric frame of reference, they do so only for two landmarks at a time, leaving it to the user to combine these binary relations into a coherent cognitive map. Moreover, they do not provide any metric information about the distance between landmarks.

It should be noted that the fact that the two navigational aids are not informationally equivalent does not imply that one representation is inherently superior to the other. As mentioned earlier, no definitive statement can be made as to which description, route or survey, is superior when it comes to acquiring spatial knowledge (Thorndyke and Hayes-Roth 1982; Taylor and Tversky 1992).

(a)

(b)

Figure 3.: **Navigational Aids:** The interface for (a) the mini-map, and (b) the verbal instructions. The route to the next destination on the itinerary can be seen highlighted on the mini-map. For the verbal instructions, directions are provided relative to a landmark in close proximity to the avatar, in this case the Fashion Boutique.

4.5. *Participants*

Thirty four participants volunteered for the experiment. Participants were paid for their time, although, three participants declined to accept payment. All participants were university students aged 18 to 24 years, with a mean age of 19.67 years. Five of the 34 participants were female, and the remaining 29 were male. While participants were informed of the general domain of research, they were not made aware of the goals of the current experiment, or that their spatial knowledge will be tested.

4.6. *Procedure*

The experiment was conducted at the Media Lab of the computing department. The learning and trial phases of the experiment, which involved interaction with the virtual environment, were run on the lab's Apple iMac computers. Participants were seated at arm's length from the 21.5 inch screen and used a mouse and keyboard to rotate and translate the first-person view, respectively. Each participant was rated on the Santa Barbara Sense of Direction (SBSOD) scale (Hegarty et al. 2002) at the start of the experiment and randomly assigned to the mini-map or verbal instructions group. The learning phase of the experiment started after a brief introduction to the game controls and the respective navigational aids.

The itinerary for the learning phase was composed of a sequence of twelve landmarks. An on-screen text message informed the participant as each landmark was reached. The respective navigational aid of each group was updated to reflect the change in destination to the next landmark on the itinerary: for the mini-map, a route to the new destination was highlighted on the mini-map; for the verbal group, verbal instructions for navigating to the new destination were displayed on screen for a period of twenty seconds.

For the map-drawing test, participants were provided with an A4 sized paper - blank except for two lines of instructions, and the cardinal directions marked in the top right corner. They were asked to draw the sketch-map as if explaining the layout of the city to a friend, and to include any information they deemed necessary. The drawn sketch-maps were taken away before the topological-ordering test. This latter test was carried out on another A4 sized paper, printed with a route map of the city, and with the position of fourteen landmarks indicated by numbered circles. The landmark-recall test was administered in an internet browser window. A quarter of the images displayed for this test were not of our experimental environment.

The trial phase required participants to navigate an itinerary composed of two landmarks. While the trial itinerary formed a subset of the itinerary from the learning task, the starting position of the participant's avatar in the virtual environment was different from the learning phase. In addition, the landmarks were presented in a different order. The small size of the itinerary was meant to prevent any spatial learning that may occur during the execution of the task from confounding the results.

No time limits were placed on the participants at any stage of the experiment.

4.7. *Measurements*

The performance of participants was judged based on the following measures

(1) The total distance D_T travelled during the trial phase.
(2) The number of landmarks ordered incorrectly for the topological-ordering test.

To recap, this test required the participant to produce an ordered list of landmarks corresponding to numbered positions on a map. The number of incorrect orderings was measured as the Hamming distance $H(s,t)$ between a string s representing the ground-truth ordering of landmarks, and a string t representing the participant's response.

The Hamming distance measures the number of corresponding positions at which two strings differ. In our case, the strings were generated by first assigning a unique letter to each landmark. String t, then, represented the ordered list of landmarks produced by the participant during the topological-ordering task (list positions left empty were replaced with an "X" - a letter not assigned to any landmark). The string s represented the ordered list of correct responses for the task.

(3) The number of unique environmental features, including landmarks, represented on the sketch-maps. Any analysis of the general quality of a sketch-map necessarily involves subjective judgments. For the current study, we chose to base our primary analysis on objective metrics only.
(4) The number of landmarks listed for the topological-ordering task.
(5) The proportion of total views correctly recalled during the landmark-recall task.

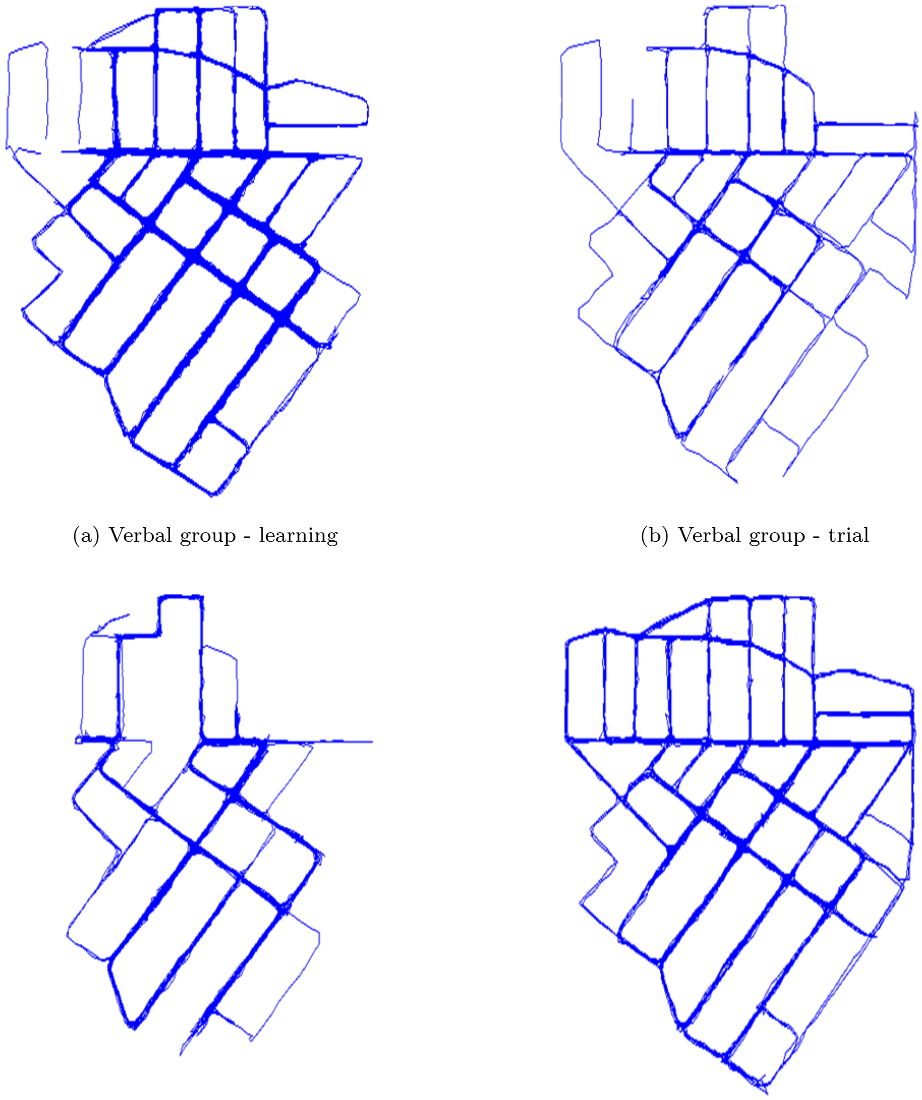
5. Results

The various performance measurements for the two groups, each with 17 participants, were compared using Welch's unequal variances t-test, $\alpha = 0.05$. The comparability of the groups was confirmed by the two groups' mean scores on the Santa Barbara Sense of Direction scale; the two means did not show any statistically significant difference at the 0.05 significance level; t(31.95) = 1.06, p = 0.29.

5.1. *Spatial Knowledge*

There was a statistically significant difference between the total distance travelled during the trial task by the verbal group (M = 1605.08, SD = 975.25), and the mini-map group (M = 4775.43, SD = 3194.50); t(18.95) = 3.91, $p < 0.01$. The effect size in this case (Cohen's d) equals 1.34, indicating a very substantial practical significance. These results suggest that participants who are given verbal instructions during the learning task, prove to be considerably more efficient wayfinders than mini-map users when no navigational aid is available. This is visually demonstrated in Figure 4 which shows the paths traversed during the learning and trial tasks by all participants in each group. Comparing the density of lines for the two conditions in the trial task, it can be seen that, for the verbal group, the thickest lines are concentrated along a relatively small number of routes around the center of the city. These were routes that led to the two landmarks on the itinerary for the task. For the mini-map group, however, near uniformly dense thick lines, indicating a high frequency of travel, are spread over most of the city.

Participants given verbal instructions, on average, included a greater number of environmental features in their sketch-maps. While the great majority of features drawn were landmarks, a few participants across both groups also included prominent props in their sketch-maps. The difference in number of features drawn by the verbal group (M = 10.588, SD = 2.47), and the mini-map group (M = 6.88, SD = 3.98) was found to be statistically significant; t(11.37) = -2.53, p = 0.02. Furthermore, Cohen's



(a) Verbal group - learning

(b) Verbal group - trial

(c) Mini-map group - learning

(d) Mini-map group - trial

Figure 4.: **Traversal Patterns:** The paths traversed by all participants in each of the two groups during the learning and trial tasks.

effect size measure (d = 1.20) suggests a very high practical significance.

A similar trend was witnessed for the topological-ordering task, and the landmark-recall task. In case of the former, there was a statistically significant difference between the average number of landmarks, out of a total of 14, listed by the verbal group (M = 10.11, SD = 2.14), and by the mini-map group (M = 7.47, SD = 3.33); t(27.30) = -2.75, p = 0.01. Again, a high level of practical significance is implied by the effect size (Cohen's d = 0.94). For the landmark-recall task, the proportion of views correctly recognized by the verbal group (M = 0.781, SD = 0.70) was significantly higher than the mini-map group (M = 0.66, SD = 0.14); t(10.17) = -2.28, p = 0.04). Cohen's effect size value of 1.14 implies a very high practical significance. Taken together, the last three results suggest that participants given verbal instructions in our proposed format are able to recall a substantially larger number of landmarks than the mini-map condition.

Testing for the number of landmarks incorrectly placed in the topological-ordering task, a significant difference in scores was found between the verbal group (M = 10.23, SD = 2.90) and the mini-map group (M = 12.33, SD = 0.70); t(19.29) = 2.82, p = 0.01. The effect size (Cohen's d) was 0.87. Hence, the verbal group placed fewer landmarks in incorrect positions as compared to the mini-map group.

5.2. *Navigational Efficiency*

On average, participants given verbal instructions travelled almost three times more distance during the learning task than participants in the mini-map condition. This difference between the scores of the verbal group (M = 14991.14, SD = 5160.81), and the mini-map group (M = 5368.04, SD = 676.91) was very highly significant indeed; t(16.55) = 7.62, p < 0.01. The size of the effect (Cohen's d = 2.61) indicates a very high practical significance to go along with the statistical significance.

6. Discussion

Collectively, the results indicate that participants in the verbal group, who were provided with landmark-based verbal navigational instructions, displayed superior spatial knowledge of the virtual environment than their counterparts in the mini-map group.

While the verbal group scored higher on the topological-ordering task, it should be noted that both groups placed more than 70% of the landmarks at incorrect positions. If, as we reasoned in Section 4, the topological-ordering task tests rudimentary route knowledge, then the poor performance of participants on this task in general may lead one to conclude that neither group develops spatial knowledge beyond the landmark stage of Siegel and White's three-stage model (Siegel and White 1975). On the other hand, it may be argued that by strictly considering the number of correctly placed landmarks, the test ignores any local consistency of topology. For instance, the triangular arrangement of one set of three landmarks may be confused for the triangular arrangement of another set. As long as the user recognized the local triangular arrangement, we cannot claim that no topological knowledge developed. Our test does not take this factor into account. Furthermore, the superior performance in the trial phase, would lead us to conclude that verbal instructions lead to a higher level of survey knowledge development.

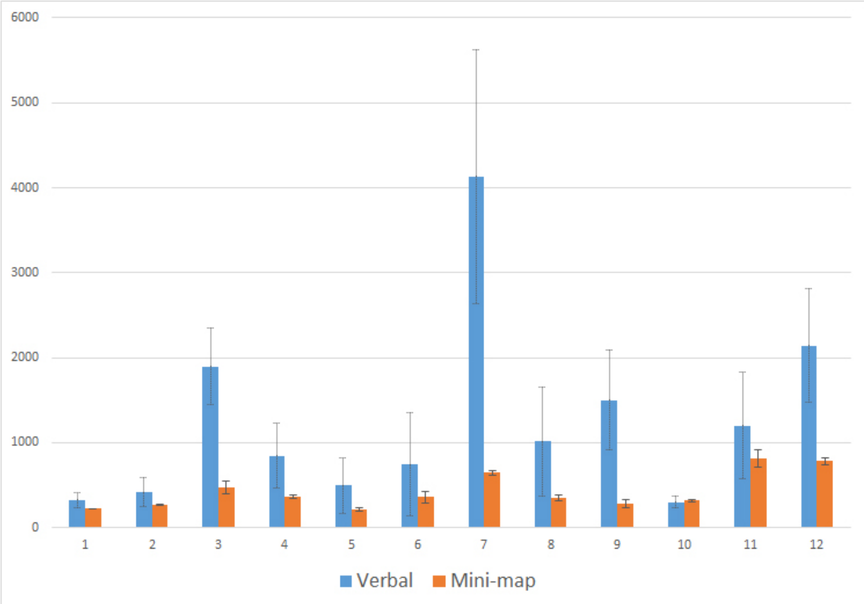


Figure 5.: **Average distance travelled per landmark:** Results are shown for the learning itinerary. The sequence of twelve landmarks in the itinerary are represented on the horizontal axis.

Results for the number of landmarks recalled by each group during the three non-navigational tasks support our claim that verbal instructions develop more persistent memory traces by requiring deeper levels of cognitive analysis.

It is evident from the results that verbal instructions lead to better spatial knowledge than mini-maps. Gardony et al. (2013) point out, however, the raison d'etre of navigational aids is *navigational efficiency*; that is, to navigate to a destination quickly and easily. The results indicate that the mini-map group was very clearly superior in this regard. However, a plot of the mean distance travelled by the verbal group for each individual landmark in the learning itinerary shows a distribution with four prominent peaks (Figure 5). This suggests that the bulk of distance was travelled searching for a relatively few landmarks. Identifying these, we found two of them (seven and nine in Figure 5) to be landmarks that were not located at street junctions. The first peak (landmark three in Figure 5), is more difficult to account for, although, a possible explanation may be that since the store sign for this particular landmark was placed at the top of the building rather than at the street-level (Figure 6), participants found it hard to locate. The fourth peak (landmark 12 in Figure 5) was the landmark with the largest source-destination distance: three and a half standard deviations greater than the mean. Since verbal instructions require participants to perform a visual search of the local environment, a larger source-destination distance implies a wider search radius and, hence, a greater number of locales that must be travelled. In fact, when landmarks seven and nine were removed from consideration, a very strong positive correlation ($R = 0.87$) was found to exist between the source-destination distance for a landmark on the itinerary, and the distance travelled by the participant to reach that particular landmark. While this may seem only natural, it does confirm that our verbal instructions, in their particular form, assist in wayfinding. This last point is important for it shows that including directional information in the verbal instructions did indeed concentrate the search area and enabled participants to navigate more efficiently

Figure 6.: **Landmark Visibility:** The A5 Studio Building - a landmark with the store sign located at the top of the building, which some participants found difficult to locate.

than a completely random search would have allowed. A final note regarding navigational efficiency is that our measure is based on the distance travelled and, hence, may not account for participants who stopped moving whenever they were lost. In our observation, however, none of the participants displayed such behavior.

It is obvious that mini-maps and our verbal instructions are *not* informationally equivalent. Therefore, it is not surprising that the verbal instructions are not as efficient as mini-maps; users of the latter aid have the benefit of an explicit route from the source to the destination, and information about how the route relates to the surrounding environment. In fact, the goal of our study was not to compare two informationally equivalent aids, but rather to explore the design parameters which affect spatial knowledge. From this perspective, one of the key results of this study is that navigational aids should not function in isolation from landmarks, which are the basic building blocks of spatial knowledge. Standard mini-maps fail to orient the user with respect to *visually* salient landmarks since the only information they provide is route knowledge and, in some cases, the location of *symbolic* landmarks such as home, office, and other areas of interest. A mini-map user has no clue that a particular route, or his/her office is situated next to the Gothic cathedral, or the Art Deco skyscraper, for instance. Hence, navigational aids designed to draw the users' attention to visually salient landmarks in the environment are likely to support the development of spatial knowledge better. As a corollary to this statement, it must be added that navigational aids that succeed in overcoming the screen center and object bias, are likely to afford the user a greater opportunity of focusing their attention on landmarks which fall in the periphery of the image.

6.1. *Design Considerations*

Our study addresses the development of survey knowledge at the geographic scale. But do all games require this form of spatial knowledge? Do all games require *any* form of spatial knowledge? To answer these questions we summarize the context in which our results hold true, and list the conditions under which a game designer should choose mini-maps over verbal instructions.

6.1.1. The role of navigation

Given the observed trade-off between spatial learning and navigational efficiency, we may deduce that spatial knowledge development is a desirable feature only if navigation is an essential component of the gameplay. In such cases, the extra effort expended during learning is justified by subsequent rewards, thereby, providing the necessary motivation to players. From a designer's perspective, this implies spatial knowledge acquisition becomes similar to any other skill that players must hone and develop as the game progresses. Hence, instructions should be restricted only to a preliminary tutorial/learning stage in order to maintain presence and the suspension of disbelief. Or, put another way, the navigational aid should *allow itself* to become redundant. As our results show, verbal instructions serve this goal better than mini-maps.

6.1.2. The environment

The survey level of spatial knowledge is desirable in open-world games, where the players have complete autonomy in selecting routes, and where the landmarks can be visited repeatedly.

The reasons for this restriction of scope are threefold. Firstly, as discussed above, independent spatial decision-making is an important factor in determining how much learning occurs (Bakdash, Linkenauger, and Proffitt 2008). Secondly, the acquisition of spatial knowledge makes sense only if it is to be subsequently put to use. And finally, the game genre should provide sufficient opportunity of interaction with the environment for learning to occur. The repetitive nature of navigation in open-world games allows individual routes and landmarks to be integrated into a common, allocentric frame-of-reference. Genres such as first-person shooters, on the other hand, involve a linear environmental progression path and, hence, do not allow such topological relations to be established.

Furthermore, as verbal instructions do not provide turn-by-turn instructions, and only vaguely relate two landmarks in a geocentric frame of reference, they should be used when the routes graph has no, or very few, leaves. In other words, there should be no dead-ends: as long as the player moves in the general direction of their destination, they should be able to reach it. Not being able to do so may lead to the player becoming frustrated.

6.1.3. The role of exploration

An additional consideration when choosing between verbal instructions and route-highlighted mini-maps is whether the designer wants to encourage, or enforce, exploration.

Darken and Cevik (1999) define exploration as a wayfinding task without a specific target. The route-highlighting feature of mini-maps implies that players can make exploratory digressions from the primary navigational task without fear of getting lost. Verbal instructions, on the other hand, do not support such digressions: players need to be cognizant of the general location of the source landmark at all times, and there is little recourse in case they get lost (one solution would be to dynamically generate verbal instructions always using a landmark close to the player as the source).

The deliberately ambiguous nature of verbal instructions, however, means that even targeted search tasks involve a degree of exploration. This is evident from Figure 4, and also from the results of the landmark recall test. Hence, while mini-maps encourage exploration, verbal instructions enforce it - albeit within a limited spatial range. This means designers must additionally consider the factor of motivation on the exploration tasks, which may possibly be higher if the tasks are presented as part of the main game narrative. For instance, how likely is a player to return to the game to find and gather a set of trophies after the "story-mode" has ended?

6.1.4. Development costs

Finally, a practical consideration when chosing a navigational aid is the relative cost of development. While a definitive measure is not possible, and would depend on the capabilities of each game engine, in our case we found that verbal instructions could be more easily implemented than mini-maps using the Unity game engine's in-built features. For the mini-maps, implementation of the route-highlighting feature required accessing the low-level graphics API. In addition, mini-maps used greater computational and memory resources compared to the verbal instructions since the path-finding feature required the storage of a graph representation of the city streets and the run-time execution of a path-search algorithm. Verbal instructions on the other hand only required trigger objects in the vicinity of landmarks that displayed a message read from a file - although, such a message could also have been programmatically generated given the name of each landmark (Figure 3b). The rotation of the compass was linked to the player camera.

7. Conclusion

Theoretical and practical evidence was presented to support the claim that mini-maps impair the development of spatial knowledge in computer games. In light of the theoretical evidence, an alternate verbal navigational aid, based on landmark-based geocentric verbal directions was proposed. The benefits of the proposed aid in terms of spatial knowledge development were demonstrated by means of a two-group randomized comparative experiment. The results of the experiment confirmed our claims on spatial knowledge. Mini-maps, however, proved superior in terms of navigational efficiency. It was suggested that positioning landmarks at street junctions, and keeping the distances between consecutive landmarks on a route small would improve the navigational efficiency of our proposed aid.

Our study has been restricted to a particular class of mini-maps: concurrent, un-moded, forward-up maps that display all navigable routes in the local environment, and provide turn-by-turn navigational instructions. This class, however, is not exhaustive. Many games use moded maps, which can only be used when the user is not navigating. Other forms of mini-maps only provide directional information, or display local topographical information without showing navigable routes. Clearly, in such cases our assumptions of increased cognitive load, and lack of spatial decision making do not hold, and alternative hypotheses are needed to explain the effects of the aid on spatial knowledge. We hope, however, that our study has shed light on some of the design parameters which govern the tradeoff between navigational efficiency and spatial learning, and provided directions for the development of future navigational aids.

Acknowledgements

The authors would like to thank Khubaib Ali Pirzada for assisting with compiling the results, Dr. Muddassar Malik who kindly consented to conducting the experiment on the machines at his lab, and the reviewers for their insightful comments and suggestions.

Authors

Numair Khan is a doctoral student in the computer science department at Brown University. Before joining Brown, Numair worked as a research associate at the National University of Science and Technology in Pakistan. He holds a Master's degree in computer science from New York University's Courant Institute of Mathematical Sciences. His research interests lie at the intersection of graphics, vision, and interaction.

Anis Ur Rahman received his Master's degree in Parallel and Distributed Systems from the Joseph Fourier University, France, and Ph.D. degree in Computer Science in 2013 from Grenoble University, France. He is now an Assistant Professor at School of Electrical Engineering and Computer Science (SEECS), National University of Sciences and Technology (NUST), Pakistan. His main research interests comprise modeling of visual attention by assessing the different mechanisms guiding it, salient multi-object image and video segmentation and tracking, and efficient implementations of large-scale scientific problems on commodity graphical processing units (GPUs).

References

Alawadhi, Ahmed, Tilanka Chandrasekera, and Chen Yang. 2014. "The effect of spatial knowledge on sense of belonging in university/academic environments." *ARCC Conference Repository* .

Aretz, Anthony J, and Christopher D Wickens. 1992. "The mental rotation of map displays." *Human performance* 5 (4): 303–328.

Aslan, Ilhan, Maximilian Schwalm, Jörg Baus, Antonio Krüger, and Tim Schwartz. 2006. "Acquisition of spatial knowledge in location aware mobile pedestrian navigation systems." In *MobileHCI '06 Proceedings of the 8th conference on Human-computer interaction with mobile devices and services*, New York, NY, USA, 105 – 108. ACM.

Baddeley, Alan. 1992. "Working memory." *Science* 255 (5044): 556–559.

Baddeley, Alan D, and Graham J Hitch. 1974. "Working memory." *The Psychology of Learning and Motivation* 8: 47–89.

Bakdash, Jonathan Z., Sally A. Linkenauger, and Dennis Proffitt. 2008. "Comparing decision-making and control for learning a virtual environment: backseat drivers learn where they are going." In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Vol. 52, 2117–2121.

Beech, John R. 1984. "The effects of visual and spatial interference on spatial working memory." *The Journal of General Psychology* 110 (2): 141–149.

Billinghurst, Mark, and Suzanne Weghorst. 1995. "The use of sketch maps to measure cognitive maps of virtual environments." In *Virtual Reality Annual International Symposium, 1995. Proceedings*, mar, 40 – 47. IEEE.

Blades, Mark. 1990. "The reliability of data collected from sketch maps." *Journal of Environmental Psychology* 10 (4): 327–339.

Blades, Mark. 1991. "Wayfinding theory and research: The need for a new approach." In *Cognitive and linguistic aspects of geographic space*, 137–165. Springer.

Borji, Ali, and Laurent Itti. 2013. "State-of-the-art in visual attention modeling." *Pattern Analysis and Machine Intelligence, IEEE Transactions on* 35 (1): 185–207.

Burnett, Gary E., and Kate Lee. 2005. "The effect of vehicle navigation systems on the formation of cognitive maps." In *Traffic and Transport Psychology: Theory and Application. Proceedings of the ICTTP 2004*, edited by Geoffrey Underwood, sep, 407–418.

Couclelis, Helen, Reginald G. Golledge, Nathan Gale, and Waldo Tobler. 1987. "Exploring the anchor-point hypothesis of spatial cognition." *Journal of Environmental Psychology* 7 (2): 99–122.

Craik, Fergus, and Robert Lockhart. 1972. "Levels of processing: A framework for memory research." *Journal of verbal learning and verbal behavior* 11 (6): 671–684.

Darken, Rudolph P., and Helsin Cevik. 1999. "CEVIK H.: Map usage in virtual environments: Orientation issues." In *In Proceedings of IEEE Virtual Reality 99*, 133. Springer Verlag.

Darken, Rudolph P., and Barry Peterson. 2014. "Spatial orientation, wayfinding, and representation." In *Handbook of virtual environments: design, implementation, and applications*, edited by Kelly S. Hale and Kay M. Stanney, 2nd ed., Human factors and ergonomics, 467–493. CRC Press.

Darken, Rudolph P., and John L. Sibert. 1993. "A toolset for navigation in virtual environments." In *UIST '93 Proceedings of the 6th annual ACM symposium on user interface software and technology*, New York, NY, USA, 157–165. ACM.

Darken, Rudolph P., and John L. Sibert. 1996a. "Navigating large virtual spaces." *International Journal of Human-Computer Interaction - Special issue on human-virtual environment interaction* 8 (1): 49–71.

Darken, Rudolph P., and John L. Sibert. 1996b. "Wayfinding strategies and behaviors in large virtual worlds." In *CHI '96 Proceedings of the SIGCHI conference on human factors in computing systems*, ACM New York, NY, USA, 142–149. ACM.

De Beni, Rossana, Francesca Pazzaglia, Valerie Gyselinck, and Chiara Meneghetti. 2005. "Visuospatial working memory and mental representation of spatial descriptions." *European Journal of Cognitive Psychology* 17 (1): 77–95.

Fenech, Elliot P., Frank A. Drews, and Jonathan Z. Bakdash. 2010. "The effects of acoustic turn-by-turn navigation on wayfinding." In *Proceedings of the human factors and ergonomics society annual meeting*, Vol. 54 of *23*, sep.

Gardony, Aaron L., Tad T. Brunyé, Caroline R. Mahoney, and Holly A. Taylor. 2013. "How navigational aids impair spatial memory: Evidence for divided attention." *Spatial Cognition & Computation* 13 (4): 319–350.

Garling, Tommy, Anders Book, and Nahide Ergezen. 1982. "Memory for the spatial layout of the everyday physical environment: Differential rates of acquisition of different types of information." *Scandinavian Journal of Psychology* 23 (1): 23–35.

Garling, Tommy, Anders Book, Erik Lindberg, and Tomas Nilsson. 1981. "Memory for the spatial layout of the everyday physical environment: Factors affecting rate of acquisition." *Journal of Environmental Psychology* 1 (4): 263–277.

Golledge, Reginald G. 1999. "Human wayfinding and cognitive maps." *Wayfinding behavior: Cognitive mapping and other spatial processes* 5–45.

Golledge, Reginald G, Valerie Dougherty, and Scott Bell. 1995. "Acquiring spatial knowledge: Survey versus route-based knowledge in unfamiliar environments." *Annals of the association of American geographers* 85 (1): 134–158.

Hegarty, Mary, Anthony E Richardson, Daniel R Montello, Kristin Lovelace, and Ilavanil Subbiah. 2002. "Development of a self-report measure of environmental spatial ability." *Intelligence* 30 (5): 425–447.

Inalhan, Göksenin, and Edward Finch. 2004. "Place attachment and sense of belonging." *Facilities* 22 (5/6): 120–128.

Ishikawa, Toru, and Daniel R. Montello. 2006. "Spatial knowledge acquisition from direct experience in the environment: Individual differences in the development of metric knowledge and the integration of separately learned places." *Cognitive psychology* 52 (2): 93–129.

Ishikawa, Toru, and Kazunori Takahashi. 2013. "Relationships between methods for presenting information on navigation tools and users' wayfinding behavior." *Cartographic Perspectives* 75: 17 – 28.

Kitchin, Robert. 1996. "Methodological convergence in cognitive mapping research: investigating configurational knowledge." *Journal of Environmental Psychology* 16 (3): 163 – 185.

Kitchin, Robert. 2000. "Collecting and analysing cognitive mapping data." In *Cognitive Mapping – past, present and future*, edited by Rob Kitchin and Scott Freundschuh, Frontiers of cognitive science, 9 – 23. Routledge.

Klauer, Karl Christoph, and Zengmei Zhao. 2004. "Double dissociations in visual and spatial short-term memory." *Journal of Experimental Psychology: General* 133 (3): 355.

Lynch, Kevin. 1960. *The Image of the City.* 1st ed., Harvard-MIT Joint Center for Urban Studies Series. MIT Press.

MacEachren, Alan M. 1992. "Application of environmental learning theory to spatial knowledge acquisition from maps." *Annals of the Association of American Geographers* 82 (2): 245–274.

Mayer, Richard E, and Valerie K Sims. 1994. "For whom is a picture worth a thousand words? Extensions of a dual-coding theory of multimedia learning." *Journal of educational psychology* 86 (3): 389.

Montello, Daniel R. 1991. "The measurement of cognitive distance: Methods and construct validity." *Journal of Environmental Psychology* 11 (2): 101–122.

Montello, Daniel R. 1998. "A new framework for understanding the acquisition of spatial knowledge in large-scale environments." In *Spatial and temporal reasoning in geographic information systems*, edited by M. J. Egenhofer and R. G. Golledge, 143–154. New York: Oxford University Press.

Moore, Gary T. 1972. "Elements of a genetic-structural theory of the develpment of environmental cognition." In *Environmental Design: Research and Practice*, edited by William J. Mitchell, 30.9.1 – 30.9.13. Los Angeles: University of California.

Moore, Gary T. 1976. "Theory and research on the development of environmental knowing." *Environmental knowing* l38–164.

Mou, Weimin, Timothy P McNamara, Björn Rump, and Chengli Xiao. 2006. "Roles of egocentric and allocentric spatial representations in locomotion and reorientation." *Journal of Experimental Psychology: Learning, Memory, and Cognition* 32 (6): 1274–1290.

Müller, Pascal, Peter Wonka, Simon Haegler, Andreas Ulmer, and Luc Van Gool. 2006. "Procedural Modeling of Buildings." In *ACM SIGGRAPH 2006 Papers*, SIGGRAPH '06, New York, NY, USA, 614–623. ACM.

Münzer, Stefan, Hubert D. Zimmer, Maximilian Schwalm, Jörg Baus, and Ilhan Aslan. 2006. "Computer assisted navigation and the acquisition of route and survey knowledge." *Journal of Environmental Psychology* 26 (4): 300 – 308.

Nash, Eric B, Gregory W Edwards, Jennifer A Thompson, and Woodrow Barfield. 2000. "A review of presence and performance in virtual environments." *International Journal of human-computer Interaction* 12 (1): 1–4.

Parish, Yoav I. H., and Pascal Müller. 2001. "Procedural Modeling of Cities." In *Proceedings of the 28th Annual Conference on Computer Graphics and Interactive Techniques*, SIGGRAPH '01, New York, NY, USA, 301–308. ACM.

Parush, Avi, Shir Ahuvia, and Ido Erev. 2007. "Degradation in spatial knowledge acquisition when using automatic navigation systems." In *Spatial Information Theory*, Vol. 4736 of *Lecture Notes in Computer Science*, sep, 238 – 254. Springer Berlin Heidelberg.

Parush, Avi, and Dafna Berman. 2004. "Navigation and orientation in 3D user interfaces: the impact of navigation aids and landmarks." *International Journal of Human-Computer Studies* 61 (3): 375 – 395.

Siegel, Alexander W., and Sheldon H. White. 1975. "The Development of Spatial Representations of Large-Scale Environments." Vol. 10 of *Advances in Child Development and Behavior*, 9 – 55. JAI. http://www.sciencedirect.com/science/article/pii/S0065240708600075.

Streeter, Lynn A., Diane Vitello, and Susan A. Wonsiewicz. 1985. "How to tell people where to go: comparing navigational aids." *International Journal of Man-Machine Studies* 22 (5):

549 – 562.

Tamborini, Ron, and Paul Skalski. 2006. "The role of presence in the experience of electronic games." *Playing video games: Motives, responses, and consequences* 225–240.

Taylor, Holly A, and Barbara Tversky. 1992. "Spatial mental models derived from survey and route descriptions." *Journal of Memory and language* 31 (2): 261–292.

Thorndyke, Perry W., and Barbara Hayes-Roth. 1982. "Differences in spatial knowledge acquired from maps and navigation." *Cognitive Psychology* 14 (4): 560–589.

Tseng, Po-He, Ran Carmi, Ian GM Cameron, Douglas P Munoz, and Laurent Itti. 2009. "Quantifying center bias of observers in free viewing of dynamic natural scenes." *Journal of vision* 9 (7): 4.

Tverksy, Barbara. 2000. "Levels and structure of spatial knowledge." *Cognitive mapping: past, present and future. Routledge, London* .

Vinson, Norman G. 1999. "Design guidelines for landmarks to support navigation in virtual environments." In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*, 278–285. ACM.

Werner, Steffen, Bernd Krieg-Brückner, Hanspeter A Mallot, Karin Schweizer, and Christian Freksa. 1997. "Spatial cognition: The role of landmark, route, and survey knowledge in human and robot navigation1." In *Informatik97 Informatik als Innovationsmotor*, 41–50. Springer.

Wiener, Jan M, Tobias Meilinger, and Alain Berthoz. 2008. "The integration of spatial information across different perspectives." In *Proceedings of the 30th Annual Conference of the Cognitive Science Society (CogSci 2008)*, 2031–2036.

Wirth, Werner, Tilo Hartmann, Saskia Böcking, Peter Vorderer, Christoph Klimmt, Holger Schramm, Timo Saari, et al. 2007. "A process model of the formation of spatial presence experiences." *Media psychology* 9 (3): 493–525.

Yeap, Wai K., and Margaret E. Jefferies. 1999. "Computing a representation of the local environment." *Artificial Intelligence* 107 (2): 265–301.

Yeap, Wai K., and Margaret E. Jefferies. 2000. "On early cognitive mapping." *Spatial Cognition and Computation* 2 (2): 85 – 116.