Guided Navigation Impairs Spatial Knowledge: Using Aids to Improve Spatial Representations

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Abstract

Successful navigation generally requires an accurate spatial representation of the environment. However, under guided navigation (i.e. route directions are provided by a GPS system or car passenger) no detailed representation of space is necessary because one only needs to follow directions. The first experiment separated components of navigation, spatial decision-making (planning and selection of routes) and navigational control (executing complex actions such as stopping and steering) for environmental learning. Spatial knowledge was assessed using multiple measures (spatial updating using immersive, head-mounted virtual reality and map construction). More accurate environmental knowledge was acquired when spatial decision-making was present at learning, $ps < .001$, $ds > .81$. No difference in spatial knowledge was found between active navigation and spatial decision-making by itself, $ps > .83$, $ds < .07$. This finding indicates that the weakened spatial knowledge with control alone (guided navigation) can be explained by the absence of spatial decision-making. Experiments 2 and 3 investigated the use of aids for ameliorating the loss of spatial knowledge for guided navigation with auditory directions. In Experiment 2, guided navigation was augmented using visual aids (primarily egocentric) which reinforced the locations of landmarks. In Experiment 3, guided navigation was augmented by adding cardinal directions (e.g. north), which are exocentric, to the auditory guidance, presented either with monaural sound or stereo sound which corresponded to environmental headings. Spatial knowledge in Experiments 2 and 3 was assessed using route replication, novel route execution, and map construction. Contrary to the hypotheses, the aids did not improve all measures of environmental knowledge. Instead, there was a match between the particular reference

frame reinforced by the aid and the relevant frame of reference for the measure of spatial knowledge. In Experiment 2, the visual aids improved accuracy for replicating routes, $p = .01$, $d = .75$, this measure is egocentric. In Experiment 3, the stereo and monaural cardinal directions improved accuracy for executing a novel route, a directional measure of survey knowledge, $ps < .06$, $ds > .52$, which is egocentric and exocentric.

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Chapter 1

1. Introduction

1.1 Overview

"After a few weeks, it occurred to me that I could no longer get anywhere without her (the GPS)."

-- D. Brooks (2007)

A global positioning system (GPS) offers an effective and easy method for guiding navigation to destinations, but it may have a substantial shortcoming. The use of a GPS system likely has a detrimental effect on encoding environmental spatial relations (e.g. locations, routes, and distances), referred to as spatial knowledge (or environmental knowledge). If a car driver uses a GPS system or has a car passenger provide route guidance to a destination, then the set of spatial decisions, such as turns, comprising the route are no longer being made by the driver. Thus, navigation is guided.

Empirical evidence indicates that guided navigation leads to an impaired spatial representation of the environment. Vehicle drivers using a GPS for route guidance report difficulty in keeping track of their current location and spatial orientation, indicating a general disengagement from the environment (Leshed, Velden, Rieger, Kot, & Sengers, 2008). In addition, experimental research has shown that guided navigation impairs the acquisition of spatial knowledge, relative to navigation where spatial choices are available, in virtual environments (VEs) (Bakdash, Linkenauger, & Proffitt, 2008; Burnett & Lee, 2005; Farrell et al., 2003; Parush, Ahuvia, & Erev, 2007) and the real-world (Ishikawa, Fujiwara, Imai, & Okabe, 2008).

Previous research has not separated control (e.g. guided navigation, a car driver that is receiving route directions from a GPS) and spatial decision-making (e.g. a car passenger providing route directions to the driver) in comparisons (Carassa, Geminiani, Morganti, & Varotto, 2002). Thus, weakened spatial knowledge with guided navigation could occur because coupled spatial decision-making and control (e.g. a car driver that is making route choices) are necessary to acquire accurate environmental knowledge. Or, it may be that only spatial decision-making is needed.

I hypothesize that environmental knowledge is impaired with guided navigation because spatial decisions are absent. The stages of spatial decision-making (action goal, retrieval of alternative places, choice of place[1], retrieval of alternative paths, choice of path, and wayfinding) require representing space (Garling & Golledge, 2000). Under guidance, it is only necessary to execute actions (e.g. steering and braking a vehicle), which do not require a representation of space (Fajen, 2005a; Warren, 2006).

How can guided navigation be augmented to ameliorate the loss of spatial knowledge? Aiding guided navigation is not straightforward. In addition to verbal guidance, GPS systems commonly offer aids such as a compass and a map, but generally these aids need to be used for making spatial choices in order to be effective (Lobben, 2007). Thus, typically these aids are ignored and a driver needs to attend to the environment, rather than frequently checking a compass or map. Consequently, users report a compass is not a helpful aid for learning a virtual town via guided navigation (Oliver & Burnett, 2008). Aids which direct attention to environmental features, like

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[1] The "choice of place" is still a part of guided navigation, but selecting a destination on a GPS system (such as entering an address) does not require spatial representation.

landmarks, have been shown to improve spatial knowledge (Oliver & Burnett, 2008; Waller & Lippa, 2007). Also, using stereo sound, as opposed to monaural sound, for guiding non-visual navigation improves performance (Klatzky, Marston, Giudice, Golledge, & Loomis, 2006). Therefore, effective aids for guided navigation increase the saliency or improve the specification of spatial relations, such as the locations of landmarks.

My dissertation has two aims. First, I investigate the impairment of environmental knowledge with guided navigation by separating the pertinent modes of learning for navigation (Experiment 1). These comparisons have been confounded in previous research. Second, I examine two types of aids for augmenting guided navigation to ameliorating the degradation of spatial knowledge. Experiment 2 has visual aids for landmarks and Experiment 3 augments auditory guidance by spatializing environmental directions (e.g. north) to correspond to heading directions, in addition cardinal directions are presented monaurally.

The dissertation structure is summarized next. Chapter 1 is a review of navigation research. This chapter includes definitions, measurement, learning modes, informational differences between components of navigation, navigation aids, and theories of navigation. In Chapter 2, the three experiments are presented. Chapter 3 is a general discussion of the theoretical and practical implications of this research.

1.2 Definitions and Concepts in Navigation

1.2.1 Components of Navigation

Navigation has two main components, spatial decision-making (travel choices, such as route planning and updating) and control (the execution of actions). These two components have been defined and conceptualized as separable (Montello, 2005)[2], but in empirical research this distinction is generally disregarded (Carassa et al., 2002). Here, active navigation is defined as coupled spatial decision-making and control, whereas passive navigation is simply observation[3]. This is analogous to a car driver deciding where to turn and controlling the vehicle (active) and a car passenger doing nothing, but looking out the window (passive). Guided navigation does not include spatial decision-making, only control (e.g. driver receiving route directions from a GPS or passenger). Conversely, navigation with spatial decision-making does not encompass control (e.g. passenger providing directions to a driver). Thus, active navigation is not unitary, see Figure 1.

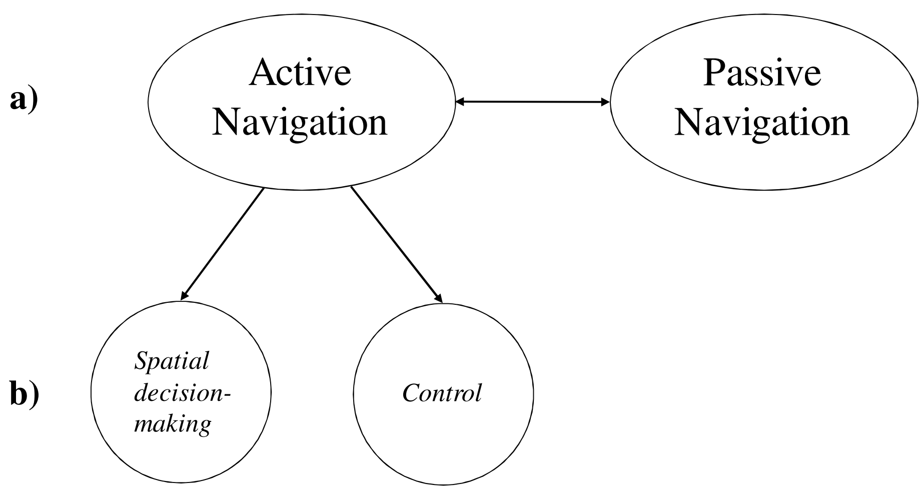

Figure 1. a) Active and passive navigation. b) Active navigation consists of two separable components, spatial decision-making and control. Note that passive navigation has neither component, making comparisons between active and passive confounded.

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[2] Montello (2005) uses different terminology: wayfinding (goal directed and planned movement) and locomotion (coordinated body movement through immediate environment). Here these terms are defined as spatial decision-making and control, respectively.

[3] Note, the terms "active" and "passive" often have varying definitions (Farrell et al., 2003). P. N. Wilson, Foreman, Gillett, & Stanton (1997) used the terms *psychological* active navigation (spatial decision-making) and *physically* active navigation (control). However, this nomenclature is not widely used. For brevity and clarity, here active navigation is defined as the two components coupled and passive navigation is the absence of both components.

1.2.2 Frames of Reference

Typically, successful travel from an origin to a destination requires a representation of space (Klatzky, 1998), However, under guidance, no representation of space is necessary. Besides the components of active navigation (e.g. guided navigation, passive navigation), there are other types of learning modes (e.g. maps, auditory verbal descriptions, and reading text). Regardless of the learning mode, in order for space to be represented it needs to be organized coherently, which is provided by frames of reference.

There are two primary types of spatial relations or reference frames, egocentric and exocentric (or allocentric) (Klatzky, 1998). An egocentric frame of reference has a viewer-centered coordinate system in that spatial relations are relative to the observer. On the other hand, an exocentric frame of reference is environmental-centered. An exocentric reference frame entails absolute spatial relations which are invariant to the location and orientation of an observer, i.e. the cardinal direction of “north” is environmentally specified, but a relative direction like “right” depends on the viewer’s orientation. At lower levels of analysis there are other types of spatial reference frames, such as in language (Levinson, 1996) and the functional organization of space around body parts (Colby, 1998; Tversky, Morrison, Franklin, & Bryant, 1999). Also, frames of reference are posited to interact in memory (Shelton & McNamara, 2001) and their coordinate systems can be transformed (Pick & Lockman, 1981). Spatial decision-making likely requires both egocentric reference frames and exocentric reference frames because it requires maintaining and acquiring knowledge of where one is (current location), where one is going (destination), and how one is going to get there (route) (Garling & Golledge, 2000).

1.2.3 Spatial Knowledge

Frames of reference specify distinct types of spatial relations, but the representation of the environment is a hypothetical multidimensional construct called spatial knowledge[4] (Golledge, 1999). In the present work, spatial knowledge refers to the representation of a large-scale environment (real or virtual), where movement is required to apprehend spatial relations because they are not all visible from a single location (Montello, 1993). Spatial knowledge is created by integrating of different sources of information (Gallistel, 1990). These cues include perceptual and cognitive processes (i.e. vision, motor, kinesthetic, and goals) (Gillner & Mallot, 1998; Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006).

Spatial knowledge for a large-scale environment can be described in three levels with the landmark-route-survey (LRS) model (Siegel & White, 1975):

1) Landmarks: unique, salient objects.
2) Routes: sequences of paths, may be connected using landmarks.
3) Survey knowledge: orientation-free, complete configural knowledge (map-like).

Originally, the LRS model was conceptualized as discrete, cumulative stages with survey knowledge only attained after extensive experience. However, the LRS model is now

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[4] In addition to spatial knowledge, there are numerous other terms which define spatial memory encoded from navigation, see Kitchin (1994). Popular terms include cognitive map, environmental knowledge, and spatial representation.

viewed as a continuous framework because the acquisition of spatial knowledge is not necessarily sequential (Ishikawa & Montello, 2006; Kitchin, 1994).

Measurement of Spatial Knowledge

There are many methods for measuring the different levels of spatial knowledge, see Kitchin (1996). Examples include sketching maps of the environment (Lynch, 1960), pointing at locations (Rieser, 1989), Euclidean distance estimation (Golledge, Briggs, & Demko, 1969; Montello, 1991), and reproducing learned routes (Siegel & White, 1975). However, the reliability and construct validity for measures of environmental knowledge have not been examined closely (Kitchin & Blades, 2002). Consequently, making direct comparisons between many navigation studies is problematic because of the use of different measures.

However, one exception to examining construct validity is the work of Allen, Kirasic, Dobson, Long, and Beck (1996). They assessed multiple measures of spatial knowledge and found the quantitative relationships for measures of spatial knowledge have a general correspondence to the qualitative LRS model.

Acquiring Spatial Knowledge

Spatial knowledge is postulated to be encoded with respect to the dominant source of information (e.g. landmarks, environmental structure, and perspective) which provides an intrinsic reference system (Mou & McNamara, 2002). For example, when the environment does not specify a single obvious structure, space tends to be organized hierarchically using clusters of landmarks (Hirtle & Jonides, 1985). Other cues may be the structure of the environment and egocentric experience (Shelton & McNamara, 2001), visibility and distinctiveness of landmarks (Steck & Mallot, 2000), and various types of salient environmental information such as neighborhoods and edges, like a river (Lynch, 1960). To improve spatial learning in VEs, design guidelines based on placement and saliency of environmental elements have been proposed (Darken & Sibert, 1996; Vinson, 1999).

1.3 Learning Modes

Different mediums or modes for learning an environment (e.g. maps versus direct experience in the environment) convey distinct sources of information influencing the acquisition of spatial knowledge (Evans & Pezdek, 1980; Thorndyke & Hayes-Roth, 1982). In the present work, the primary focus is on navigation in VEs from a first-person perspective (direct experience). The relevant learning modes for guided navigation are comparisons between the components of active navigation.

1.3.1 Virtual and Real Environments

Overall, navigation in VEs leads to spatial representations similar and perhaps even equivalent to learning in the real-world (Ruddle, Payne, & Jones, 1997; Waller, Hunt, & Knapp, 1998; Williams, Narasimham, Westerman, Rieser, & Bodenheimer, 2007). This is supported by individual differences in navigation ability having a stronger influence on acquiring spatial knowledge than whether the environment is virtual or real (Darken & Banker, 1998). A related finding was made by Waller (2000), individual differences in spatial ability and interface (control) proficiency for VEs were the largest predictors of environmental learning. However, there is evidence that attaining survey knowledge in a highly complex VE (i.e. a building with two floors) may be more difficult than real-world learning (Richardson, Montello, & Hegarty, 1999). Nevertheless, VEs are a valid tool for studying navigation (Waller et al., 1998). Not surprisingly, the quality of graphics of VEs is also important for acquiring spatial knowledge (Lessels & Ruddle, 2005; Waller et al., 1998; Waller, Knapp, & Hunt, 2001).

1.3.2 Active and Passive Navigation

For both real-world and virtual learning, there are sometimes inconclusive findings for comparisons between active navigation and passive navigation (P. N. Wilson & Péruch, 2002). In the current work, active navigation is defined as spatial decision-making and control, whereas passive navigation is simply observation, like watching a video being played. Most research comparing active and passive navigation find that active leads to more accurate spatial knowledge (Appleyard, 1970; Downs & Stea, 1973; Péruch, Vercher, & Gauthier, 1995), although the advantage for active can be limited to particular measures of spatial knowledge (B. M. Brooks, Attree, Rose, Clifford, & Leadbetter, 1999; Péruch & Wilson, 2004). In other studies, active and passive navigation have been reported to result in comparable spatial representations (P. N. Wilson, 1999; P. N. Wilson, Foreman, Gillett, & Stanton, 1997). Comparisons between guided navigation (control only) and passive navigation (neither spatial decision-making nor control) are also mixed, with control reported to improve spatial knowledge (Sun, Chan, & Campos, 2004; Wallet, Sauzéon, Rodrigues, & N'Kaoua, 2008) or no differences reported (Gaunet, Vidal, Kemeny, & Berthoz, 2001). Generally, more accurate spatial knowledge is acquired with active navigation compared to guided navigation (Bakdash et al., 2008; Burnett & Lee, 2005; Carassa et al., 2002; Farrell et al., 2003; Ishikawa et al., 2008).

Explanations for Active and Passive Navigation Findings

The variety and inconsistency of findings active and passive navigation, has led to the proposal of a unifying explanation, attention (P. N. Wilson & Péruch, 2002). This proposal states that there are no differences between learning modes when attention is high, implying the level of attention is more important than the mode of learning. However, this is a partial explanation since differences between learning modes still occur even attention is postulated to be equivalent across conditions (Farrell et al., 2003). Besides attention, there are other explanations. It is difficult to compare studies because measures of spatial knowledge are disparate (Péruch & Wilson, 2004; Wallet et al., 2008) and there are variations in environmental complexity (Wallet et al., 2008).

For passive navigation, there is a lack of interaction between the motor system and the environment (Downs & Stea, 1973). This explains the frequent advantage for active navigation over passive navigation and is supported by developmental research on the importance of self initiated movement for perceiving the consequences of acting in the environment (Bertenthal & Campos, 1990; E. J. Gibson & Walk, 1960; J. J. Gibson, 1979; Held & Hein, 1963). Similarly, B. M. Brooks et al. (1999) proposed that the interactivity in active navigation, the coupling of control and being able to decide where to go, directs attention relevant to environmental features which enhances memory over passive navigation. Still, interactivity does not address why sometimes there are no differences in environmental knowledge for active versus passive learning.

Related to interacting with the environment, P. N. Wilson and Péruch (2002) suggested that attention, perhaps as a by product of interactivity for learning modes (e.g. active versus passive navigation, guided versus passive navigation), is what matters for learning an environment. Thus, the inconsistent findings for active and passive navigation are a result of variations in attention. Paralleling this reasoning, Parush et al. (2007)

stated that automatic nature of navigation systems made participants “mindless” of the environment.

P. N. Wilson & Péruch (2002) also postulate that advantages for active versus passive navigation emerge when spatial knowledge is tested incidentally (i.e. during learning participants were unaware they would assessed), but tend to disappear with explicit instructions because there is a high level of attention during learning. This claim is supported by the influence that experimental instructions (i.e. specific goals such as learning routes, remembering the location of a particular object versus incidental testing of spatial knowledge) have on the accuracy and structure spatial knowledge (Rossano & Reardon, 1999; Taylor, Naylor, & Chechile, 1999). Thus, it seems plausible that attention to relevant environmental features, such as landmarks, is reduced for less interactive learning modes (e.g. guided navigation, passive navigation) and incidental testing, leading to weakened spatial knowledge.

However, attention cannot be a comprehensive explanation for spatial knowledge deficits with guided navigation. When participants receive instructions that explicitly specify how spatial knowledge will be assessed, environmental knowledge is still more accurate for active navigation relative to guided navigation (Farrell et al., 2003) and active navigation and navigation with spatial decision-making compared to guided navigation (Experiment 1). Regrettably, in many navigation studies it is unclear if spatial knowledge was tested incidentally, making it unexpected, or if it was anticipated because it was explicitly included in the instructions. In addition, there are numerous other factors which influence the acquisition of spatial knowledge, such as individual differences (spatial ability and control proficiency in VEs), how spatial knowledge is measured, and environmental complexity. Regardless, active navigation is not unitary; it has two components, so comparisons between the learning modes of active navigation are either confounded or incomplete.

1.3.3 Guided Navigation and Spatial Decision-Making

Spatial knowledge is degraded for guided navigation compared to active navigation (Bakdash et al., 2008; Burnett & Lee, 2005; Carassa et al., 2002; Farrell et al., 2003; Ishikawa et al., 2008). However, since navigation has two components, less accurate spatial representations under guidance (control alone) could be due to the lack of coupled spatial decision-making and control (active navigation) or simply the absence of spatial decision-making. Consequently, the confounded nature of comparisons between navigation components has been overlooked (Carassa et al., 2002). As mentioned earlier, interactivity and attention have some relevance on learning an environment, but are unlikely to be a primary explanation when instructions are explicit on how spatial knowledge will be assessed.

I propose that spatial decision-making facilitates the acquisition of spatial knowledge. This is because there are distinct informational differences between spatial-decision-making and control. Spatial decision-making requires creating and updating of representations of environmental layout (Garling & Golledge, 2000), which specify spatial relations. For control, no such spatial representation is necessary. Perception and action research has shown that optic flow (the pattern of visual motion created with movement) is sufficient for performing actions (Fajen, 2005a; Lee, 1976; Warren, Kay, Zosh, Duchon, & Sahuc, 2001). Optic flow fully specifies the spatial layout of the environment (i.e. its structure) (J. J. Gibson, 1979). Thus, actions can be performed using invariants in optic flow, which consists of the visual angles and the rate of change of visual angles using control heuristics that are outside of conscious awareness. Spatial representations can still be acquired in the absence of goals (Gillner & Mallot, 1998), so there is acquisition of spatial knowledge with guided navigation, albeit diminished. Finally, another potential reason for impaired spatial knowledge with guided navigation is that performing a spatial verbal task causes interference in spatial memory (Salthouse, 1974). However, this is a speculative reason since the cognitive load for following directions during navigation has not been compared to methods for selective interference.

1.4 Informational Differences between Spatial Decision-Making and Control

The informational differences between the components of navigation can be summarized as follows; spatial decision-making requires creating and updating spatial representations, but no creation of spatial representations are specified with control because online visual information is sufficient to perform actions. These informational differences are supported by perception and action research. The perception of spatial layout (i.e. distances and slants) are influenced by factors that are similar to spatial decision-making, such as intention to act, consequences for action, and action planning (Proffitt, 2006). Whereas for control, complex actions relevant to navigation, like walking (Warren et al., 2001) and stopping in time to avoid hitting an obstacle (Lee, 1976), can be executed without needing a spatial representation by using visual control heuristics, for reviews see Fajen (2005a) and Warren (2006).

In contrast to visual control heuristics, Loomis and Beall (1998) have proposed a multilevel model of control, positing representations are necessary to perform actions. Their account postulates that many actions are too complex for visual information to be sufficient: thus, both internal representations of action capabilities and a spatial representation of the environment are necessary. However, the Loomis and Beall model of perception and action assumes spatial decision-making and control are intertwined, which is not always the case because the components of navigation are indeed separable.

1.4.1 Spatial Decision-Making

In navigation, spatial decision-making broadly consists of "… choices of future courses of action" (Garling & Golledge, 2000, p. 44). Goal direct travel (route traversal to a destination) requires the creation and updating of spatial representations; knowledge of where one is, where one is going, and how one is going to get there. Thus, spatial decision-making occurs in stages, possibly through hierarchically, interconnected with spatial representations (Garling & Golledge, 2000). The spatial choices made for learning an environment are not random (Giudice, Bakdash, & Legge, 2007), nor do they reach normative optimality, likely due to the limitations and inaccuracies inherent to integrating and updating of spatial locations during exploration (Stankiewicz, Legge, Mansfield, & Schlicht, 2006).

Perception of Spatial Layout

Garling, Book, and Lindberg (1984) state that spatial decision-making plans for action, like route planning and executing physical actions for travel, are important for acquiring spatial representations. Similarly, the costs, goals, and possibilities for acting in environments influence the representation of spatial layout (i.e. distances and slants) (Proffitt, 2006). For example, Witt, Proffitt, and Epstein (2005) showed that a tool extending reach made targets that were previously out of range appear closer compared to when no tool was held. However, if there was no intention to reach to targets with the tool, perceived distance was unaffected. Other work has shown there is only an effect of physical effort on perception for the affected and intended goal, thus distance perception is action specific (Witt, Proffitt, & Epstein, 2004). While assessing the possibilities for action entails representing space, the actual execution of the action does not. That is, making the decision to perform an action (e.g. reach to a target, plan a route) can precede or occur concurrently with executing the action, but performing the action itself does not require spatial representation because online visual information is sufficient.

At first glance, coupled spatial decision-making and control appear to be more interactive than the former alone. However, even with only spatial decision-making the motor system is active, given that planning and intending to act elicits motor simulation (Witt & Proffitt, 2008). That is, simulated or imagined actions tend to have common temporal properties and overlapping neural activation with the performance of actions (Jeannerod, 1997). Consequently, the “interactivity” for spatial decision-making shares, at least some, communalities with active navigation.

1.4.2 Neural Activation for Spatial Decision-Making

There is additional evidence for separating the control and decision-making components of navigation based on increased patterns of brain activity for spatial decision-making. These patterns suggest that spatial decision-making results in greater facilitation of creating and updating spatial relations. There is increased activation in the left hippocampus (associated with computing heading direction and maintaining, updating, and recollecting an exocentric spatial representation) for navigation with spatial decision-making compared to navigation guided by following a trail (Maguire et al., 1998). Also, there are specific cells in the right hippocampus and right amygdala which encode the spatial locations of objects and landmarks which are relevant to navigational goals (Ekstrom et al., 2003). The importance of landmarks at decision points (e.g. intersections) is further reflected by their association with increased activation in parahippocampal gyrus (associated with encoding the spatial locations of objects), which is independent of attention (Janzen & van Turennout, 2004). Finally, the separability of spatial decision-making and control are consistent with the neural and behavioral dissociations in the two visual streams for perception and action (Goodale & Milner, 2005; Milner & Goodale, 1995). Overall, the patterns of brain activity suggest spatial decision-making is associated with additional encoding and updating of spatial relations.

1.4.3 Control Using Visually Guided Actions

The idea that actions can be performed without spatial representation may seem paradoxical, but for many and maybe all situations, optic flow (the pattern of visual motion created with movement) is sufficient to fully specify the spatial layout of the environment (J. J. Gibson, 1979). Visually guided actions relevant to navigation include steering and braking to avoid hitting an obstacle. Warren, Kay, Zosh, Duchon, and Sahuc (2001) showed that walking towards a location uses a weighted combination of optic flow and egocentric direction based on the quality of information in each variable. Similarly, slowing down to avoid hitting an obstacle follows a simple heuristic, tau-dot, the derivative of the relative rate of expansion for the optical angle of the obstacle (Lee, 1976). The challenging action of catching a fly-ball in baseball is performed using a visual control heuristic, linear optical trajectory, which is running to nullify the perceived curved trajectory of a fly-ball (McBeath, Shaffer, & Kaiser, 1995). Another control heuristic has been proposed for fly-ball catching, optical acceleration cancellation. This heuristic entails running to cancel the vertical acceleration of the ball's projected angle (Fink, Foo, & Warren, 2009).

Actions can be changed or stopped during execution either due to conscious choice (e.g. choosing an alternative route or changing the destination), but the visual control heuristics for executing an action are unconscious. Therefore, no elaborate stereo representation of spatial layout is necessary for navigational control of actions like steering and stopping.

1.4.4 Control Requiring Spatial Representations

In contrast, Loomis and Beall (1998) propose that optic flow alone is not sufficient for the guidance of actions because control heuristics are limited to primitive actions, thus representations of the environment and of action capabilities are necessary. In addition, unlike the current work, this model specifies the two components of active navigation are not separable. This model contains multiple levels for visually controlled locomotion, consisting of: selection of a destination and creating a planned route using representation of space, following and updating the route based on visible environmental layout, and control of variables such as speed and heading. The first two levels of the model correspond with decision-making (i.e. selecting a destination, route updating, and planning). However, the third level of their model corresponds to, what is here defined as control. At the third level, there is convincing evidence that actions relevant to navigation can be executed using visual control heuristics (Fajen, 2005a; Warren, 2006).

At the third level of the model, there is also internal representation of action capabilities is called plant dynamics. For example, the plant dynamics for driving a car would be internal representations of its steering radius, physical size, and acceleration and braking capabilities. However, there are examples of visually guided actions that incorporate control constraints (Kim & Turvey, 1999; Wann & Swapp, 2000) and evidence that visual information is sufficient for rapid recalibration of action capabilities (Fajen, 2005b). Therefore, plant dynamics may not be necessary for performing actions. Finally, the components of active navigation, while often coupled (Montello, 2005), are clearly separable, as conceptualized in the present work.

1.4.5 Summary

The information used in making navigational choices consists of creating and updating spatial representations, both of which facilitate the acquisition of environmental knowledge. Control – the visual guidance of actions – consists of feedforward and feedback heuristics that apply directly to optic flow as opposed to stereo representations of spatial layout. Navigational choices establish a link between the environment and the self. Control has no such link; it involves achieving proximal goals, such as executing a turn. The interactive nature of spatial decision-making fits with embodied cognition, a theoretical framework postulating that cognitive processes are associated with bodily states, capabilities, and interaction with environment (M. Wilson, 2002). Similarly, the perception of spatial layout also reflects embodied cognition, as it is influenced by the relationships between intentions, action capabilities, and the environment. Furthermore, the neural activation associated with spatial decision-making indicates that it facilitates the acquisition of environmental knowledge. How can the loss of spatial knowledge under guided navigation be ameliorated?

1.5 Augmenting Navigation Using Aids

Navigation aids serve several related purposes; assisting with environmental learning, reducing the probability of getting lost, and helping with travel to a destination. Navigational guidance to a destination can be viewed as an aid too because it meets the latter two purposes, albeit at the cost of impairing spatial knowledge (Burnett & Lee, 2005; Chen & Stanney, 1999). Traditional aids include a compass and a map. These aids are effective when used to make navigational decisions (e.g. planning a route, directional heading). Other types of aids consist of environmental design guidelines, often with a focus on landmarks. Navigation aids can be descriptively classified into a hierarchy of different levels, based on the amount of information that is provided (Chen & Stanney, 1999).

Few studies have investigated aids for improving spatial knowledge with guided navigation. However, improving spatial representations for guidance requires aids that draw attention to elements in the environments, like landmarks, and/or updating of environmental spatial relations. Thus, in the current work, I hypothesize that the environmental knowledge acquired from guided navigation can be improved by using visual aids that make landmarks more salient and provide information about their spatial relations (Experiment 2) and by augmenting auditory guidance by spatializing cardinal directions (e.g. south) to correspond to heading directions in the VE (Experiment 3).

1.5.1 Traditional Aids

For active navigation via free-exploration (i.e. unrestricted search of the environment through discovery), traditional aids (e.g. map, compass) have minimal benefit to spatial knowledge when used alone, but can be marginally effective when combined (Ruddle, Payne, & Jones, 1998, 1999). These aids are helpful when they are used to assist with making *precise* spatial choices (Lobben, 2007), such as planning a route to a destination or keeping track of the direction of the origin to avoid getting lost. However, under guided navigation spatial choices are absent. Accordingly, spatial knowledge for guided navigation is still deficient even with a map and compass available (Oliver & Burnett, 2008).

1.5.2 Landmarks Aids

Besides traditional aids, there are numerous design guidelines for virtual environments (Darken & Sibert, 1993; Vinson, 1999). The majority of the design guidelines are based on the spatial elements of paths, edges, districts, nodes, and landmarks identified by Lynch (1960). Out of these spatial elements, landmarks tend to be most commonly used and reliable aid for organizing spatial relations (Presson & Montello, 1988; Ruddle et al., 1997; Siegel & White, 1975).

There are two types of landmarks, beacon/global (distal) and local (proximal) (Steck & Mallot, 2000; Waller & Lippa, 2007). Beacon landmarks are highly visible, such as a mountain or tall building. Local landmarks, are locations at decision points, with limited visibility (i.e. cannot be seen from other places in the environment). They may serve as associative cues, denoting that the decision point is the place to turn and also providing orientation information for precise turn directions (Waller & Lippa, 2007). Landmarks which are persistent, perceptually salient, and informative are heavily relied upon during navigation, but poor landmarks lead to greater reliance on environmental structure (i.e. the grid layout of a city) (Stankiewicz & Kalia, 2007). Lastly, beacon landmarks are a more effective aid for active navigation than local landmarks, but with a limitation. The efficacy of beacon landmarks is dependent on their availability, whereas local landmarks tend to promote more enduring route knowledge even after they are removed (Waller & Lippa, 2007).

Transforming local landmarks into beacon ones, by increasing their sizes, leads to faster travel time between locations in a virtual environment with active navigation (Pierce & Pausch, 2004). Beacon landmarks are effective aids for learning with active navigation, although directional information is not necessarily encoded (Waller & Lippa, 2007). Consequently, when an environment is learned with beacon landmarks, which are subsequently removed, route knowledge becomes less accurate compared to learning with local landmarks (Waller & Lippa, 2007). Thus, beacon landmarks may promote configural knowledge, which is orientation-free, but without encoding of directional information.

This phenomenon is analogous to having a map of landmarks with only a single landmark visible in the environment. There is no specified correspondence between the orientation of the map and the egocentric viewing orientation of the environment. Thus, spatial knowledge created with beacon landmarks may be contingent on having at least two landmarks visible or awareness of environmental directions, such as north, to correctly align a map.

1.5.3 Auditory Aids

Spatial audio has been used as an aid for navigation with vision (Lokki & Grohn, 2005) and without vision (Giudice & Tietz, 2008; Klatzky et al., 2006). With vision, virtual targets are actively navigated to faster with the addition of a stereo sound aid corresponding to target orientation and distance (Lokki & Grohn, 2005). The advantages of stereo sound for non-visual navigation have been attributed to the spatial congruency between the verbal descriptions of the environment layout and the physical structure of the environment (Giudice & Tietz, 2008; Klatzky et al., 2006). For navigation without vision, an example of stereo sound would be the verbal description of "There is a 40 foot hallway to your left" is heard in the left ear as opposed to a monaural sound. When an environment is learned without vision via monaural verbal descriptions, spatial knowledge is impaired relative to sighted navigation (Giudice, Bakdash, Legge, & Roy, 2010), but this detriment can be reversed using spatial audio (Giudice & Tietz, 2008). An additional benefit of stereo sound is that it has lower demands on working memory than monaural sound (Klatzky et al., 2006).

Cardinal Directions

Cardinal directions (i.e. north, south, east, and west) have the advantage of being environment-centered, making them absolute and viewpoint invariant. That is, regardless of an individual's egocentric orientation, north is always north. However, making judgments using cardinal directions is difficult for many, so errors are frequent (Gugerty & Brooks, 2001, 2004). Gugerty and Brooks (2001) suggest that the accuracy of cardinal directions can be improved by visually integrating them into an egocentric view (e.g. a compass in the heads-up display of an aircraft that is superimposed on the ground plane). Interestingly, good navigators tend to use cardinal directions more often than poor navigators, who primarily rely on egocentric directions (Baldwin & Reagan, 2009).

1.5.4 Aids for Guided Navigation

Few studies have examined aids for guided navigation. Oliver and Burnett (2008) improved spatial knowledge for guided navigation in a driving simulator by including descriptions of landmarks in the turn directions. For example, “In 50 yards turn right” was augmented by including the landmark at a decision point “In 50 yards turn right, at the church.” This type of aid has the drawback of requiring, ideally, a single unique landmark at every intersection. Parush et al. (2007) took a different approach for aiding guided navigation, memory rehearsal for maintaining and updating spatial knowledge. Participants periodically performed an orientation task, reporting their current position relative to other locations. While this aid was effective, it is obtrusive and reduces the ease of use of a navigation system.

1.6 Theories of Navigation

Like the emphasis the literature on navigation aids often places on the environment, navigation theories tend to focus on external, environmental information and perspective. Hence, the internal state of spatial decision-making is not included. Garling and Golledge (2000) note this problem, the processes of making spatial decisions in navigation have not moved beyond description, even calling their own framework tentative. Also, many theories of navigation are primarily based on studies with small environments, rather than environments that require translation, in addition to rotations, for acquiring spatial representations. The applicability of these theories to navigation in large environments, while plausible, is not certain.

One framework primarily dealing with the relevance of environmental information is the intrinsic frame of reference theory (Shelton & McNamara, 2001, 2004). It postulates space is encoded using reference directions from the most salient information available. This information can include environmental structure (Kelly & McNamara, 2008; Mou, McNamara, Valiquette, & Rump, 2004; Stankiewicz & Kalia, 2007), environmental features (McNamara, Rump, & Werner, 2003; Stankiewicz & Kalia, 2007), and egocentric experience (Kelly & McNamara, 2008; Shelton & McNamara, 2001). Granted, decision-making could be viewed as a salient source of information, but internal states are not posited as variables in the intrinsic frame of reference theory.

Other navigation theories describe and categorize spatial representations. This includes levels of spatial knowledge and the order of their acquisition (Siegel & White, 1975) and the role of orientation in the encoding and retrieving spatial representations (Waller, Montello, Richardson, & Hegarty, 2002). The current conceptualization of spatial decision-making fits with a theory positing a dual memory system for spatial representations (Waller & Hodgson, 2006). This theory postulates a precise, online, and transient spatial memory system and a coarse, unlimited capacity, and enduring system. Under this framework, information that is reduced or disrupted may result in a switch from the precise system to the imprecise system (Waller & Hodgson, 2006). Therefore, it is possible that under guided navigation the coarse memory system is used because the input information is impoverished, thus no or limited encoding occurs with the precise system.

However, most of the empirical evidence for these two theories, the intrinsic reference frame and dual memory system, use small-scale or medium-scale environments (e.g. unoccluded objects in a room). For small and medium sized spaces, there is at least one perspective where all spatial relations are visible. In contrast, navigation here is discussed for large-scale environments; where apprehending space requires integrating multiple perspectives via translations and rotations. Thus, the relevance of these two theories to my dissertation is limited; abilities for small-scale and large-scale environments are partially dissociable (Allen et al., 1996; Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006). Furthermore, in a number of the studies supporting the previously mentioned theories, some of the dependent measures (latency and accuracy for rotational perspective taking) are strongly associated with small-scale rather than large-scale spatial ability.

Consequently, there is not a clear fit between theories in navigation and spatial decision-making and guided navigation. Instead, the informational differences between components of active navigation have greater relevance; particularly environmental representation for spatial decision-making (Garling & Golledge, 2000), an embodied approach to perception (Proffitt, 2006), and the sufficiency of online visual information for executing control actions (Fajen, 2005a; Warren, 2006).

Chapter 2

2. Experiments

2.1 Overview of Experiments

The first experiment separated components of active navigation, comparing environmental knowledge for learning between active navigation, spatial decision-making, and control. For active navigation, the participant decided where to go and had control. In the decider condition (spatial decision-making), the participants verbally instructed the experimenter, whom had control, where to go. Participants in the controller condition (only control, which is guided navigation) followed the verbal directions of the experimenter, based on recorded paths of deciders. Thus, visual information between deciders and controllers was matched. Based on the informational differences between spatial decision-making and control, I hypothesized that deciders would acquire spatial knowledge comparable to active learning because making spatial choices requires a representation, but control does not. Consequently, I also hypothesized that controllers would have less accurate spatial knowledge than the other conditions.

Experiments 2 and 3 incorporated navigation aids to ameliorate the loss of spatial knowledge with guided navigation. For these studies, the guidance was auditory and either augmented with navigation aids or not. In Experiment 2, two types of visual aids are used; a dynamic signpost indicating the direction and distance of landmarks relative to the navigator and a visual indicator to turn local landmarks into highly visible beacons. The visual aids are shown in Figure 2.

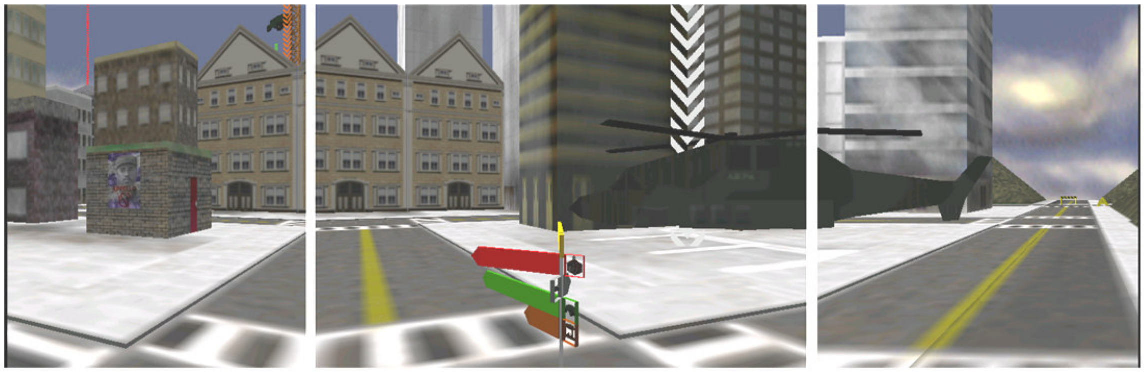

Figure 2. The arrow's pointing direction indicates orientation to a target, based on current heading. Length of the arrow depicts the distance of a target, based on current location. Note, the beacon aid is also shown, depicted by the vertically oriented arrows.

For Experiment 3, the aid was spatializing the auditory guidance of cardinal directions (e.g. "Turn right, heading north" is heard in the right ear). Also, cardinal directions were presented using monaural sound.

Navigation Aids for Experiments 2 and 3

The visual aids for Experiment 2 augmented landmarks in the environment, which is motivated by prior research demonstrating the importance of landmarks (Presson & Montello, 1988; Ruddle et al., 1997; Siegel & White, 1975). Expressly, the beacon aid increased the saliency of landmarks by making them visible over greater viewing distances, even when such landmarks would be otherwise occluded. Although beacon landmarks are strong aids while navigating towards a location (Pierce & Pausch, 2004), they may not provide persistent directional information for route knowledge, meaning route knowledge could be less accurate if the beacons are removed (Waller & Lippa, 2007). The dynamic signpost aid offered complementary spatial information to the beacon aid by specifying egocentric spatial relations to landmarks (locations relative to the viewer). In addition, it provided information relevant to route learning, the exocentric spatial relations (landmark relative to landmarks) with respect to current location and orientation. Efficacy for this aid is supported by prior research where guided navigation was successfully augmented by drawing attention to landmarks. Specifically, the effective augmentations involved adding landmarks to guidance directions (Oliver & Burnett, 2008) and requiring navigators maintain and update the spatial locations through periodic rehearsal (Parush et al., 2007). I hypothesize that the visual aids for guided navigation will improve the accuracy of route and survey knowledge.

The auditory aid for Experiment 3 enhanced learning by spatializing the cardinal directions in the verbal guidance instructions; this created a direct correspondence between orientation and the environment. In contrast, monaural presentation of cardinal directions likely has greater spatial integration demands (e.g. navigators may need to know their previous heading in order to correctly update current and future environmental heading directions). Thus, using cardinal directions may require constant updating. This limitation fits with prior research showing that cardinal directions are typically ignored because they are difficult and confusing to use (Gugerty & Brooks, 2001, 2004). However, spatializing auditory navigation guidance reduces demands on working memory (Klatzky et al., 2006), which is a likely explanation for why non-visual navigation with stereo auditory descriptions of space result in more accurate environmental knowledge than monaural descriptions (Giudice & Tietz, 2008). Also, when spatial relations are effectively learned using environmental coordinates, spatial knowledge is more accurate than with egocentric learning (Féry & Magnac, 2000). In addition to spatialized cardinal directions in guidance, Experiment 3 included two other baseline guidance conditions; cardinal directions presented monaurally and egocentric monaural guidance. I hypothesize that spatialized cardinal directions will result in more accurate route and survey knowledge than the other two conditions, which are proposed to be comparable.

2.2 Measurement of Spatial Knowledge

In all three experiments, prior to learning the environment, participants received explicit instructions on how spatial knowledge would be assessed. Instructions were explicit in order to minimize the likelihood that mindlessness or lack of attention could influence the results.

Spatial knowledge was assessed using two measures in each experiment. Experiment 1 used two transfer task measures (assessment in a different mode for learning). The first measure was spatial updating, pointing at out-of-sight locations, assessed in head-mounted (HMD) virtual reality (VR). Pointing error is a general assessment of spatial knowledge, indicating route knowledge (the path between locations has been traversed) and survey knowledge (pointing from a novel perspective or pointing between locations where the path was never traversed directly). The second measure was a map task which entailed positioning the locations of targets on a blank screen, the map. It is a measure of survey knowledge, albeit a partial one because an accurate map can be constructed without apprehension of combined absolute and relative spatial relations. That is, an accurate map can be created without being able to match its orientation and locations to the egocentric locations and egocentric orientation in the environment.

The primary benefit of transfer task measures is they provide evidence that spatial knowledge is not limited to mode of learning. For example, transfer task measures can suggest that virtual learning may transfer to real-world navigation and learning via direct experience to constructing a map. A potential disadvantage of transfer task measures is they may not be relevant for the level of spatial knowledge of interest. For example, as explained above, constructing an accurate map may be an irrelevant measure for being able to traverse routes between locations. These tradeoffs reflect the nature of spatial knowledge; it is a multidimensional construct (Golledge, 1999).

Measures for Experiments 2 and 3

For Experiments 2 and 3, the map construction measure was used again, but spatial updating was not. Spatial updating may be an indirect measure of navigation performance because being able to point at locations does not ensure they can be traveled to without getting lost. Therefore, route knowledge was instead assessed more directly by measuring the accuracy for reproducing learned paths (travel between locations experienced during learning). Thus, the more direct measure of route knowledge is a better indicator of navigation performance, if traversing paths between locations is the outcome of interest. Also, an aspect of survey knowledge was assessed by having participants traverse a novel path between the target locations that was never experienced at learning. Last, a transfer task measure, map creation, was included with both of the experiments on aiding guided navigation.

Nevertheless, there are disadvantages for the route measure used in Experiments 2 and 3. First, there is the potential for feedback, resulting in additional learning during testing. Second, since route knowledge was assessed in the same mode as learning (desktop VE), claims about the generalizability of spatial knowledge to other modes are limited. The second shortcoming is not a huge weakness, given the strong similarities between navigation and VEs in the real-world (Waller et al., 1998).

2.3 Experiment 1: Separating Components of Active Navigation

Method

Participants

Sixty-seven University of Virginia students and members of the Charlottesville community (34 male, 33 female, mean age = 19.50) participated in this experiment. Participants were either paid $20 or received course credit for their participation. Seven participants were excluded from the study; five participants experienced motion sickness in VR, one was visibly intoxicated, and one was excluded due to a malfunction with VR tracking. All excluded participants were replaced.

Equipment

Alice99 was used to create and render the virtual city which was viewed from a first-person perspective, see Figure 3.

Figure 3. Example screenshot of the virtual city from the same viewpoint seen by participants.

This is the same virtual city that was used in an earlier navigation study (Bakdash, Augustyn, & Proffitt, 2006). The VE consisted of streets laid out in an irregular grid and measured approximately 150 meters by 200 meters in size. Five target objects (gazebo, tank, school, helicopter, and humvee) were situated in the environment such that only one was visible at a time.

Practice and Learning Phases. The purposes of the practice phase were to familiarize participants with the joystick control (active and controller conditions) or rehearse verbal directions with the experimenter (decider condition). In the active and controller conditions, participants used a Saitek Cyborg EVO joystick to control their movement through the VE. Heading direction (rotation) was adjusted by moving the joystick and the throttle of the joystick controlled walking speed (translation). In the decider condition the experimenter used the joystick to control movement, following the verbal directions from the participant. Trajectory data from each participant in the decider was recorded. The experimenter viewed the paths taken by decider participants on a Dell Latitude C610 laptop and gave verbal directions to controller participants to follow the same paths, creating matched pairs. Although the experimenter was seated next to controller participants, in order to keep the participants attention on the projected screen, the experimenter tilted the laptop screen away from participants so that it was only visible to them.

During the practice and learning phases, the virtual city was learned on a large projected screen (desktop VE). The practice phase of the experiment used a VE that was similar in appearance to the actual city environment, but was much smaller and did not contain any target locations. The VE was rendered at 640 by 480 and 60 frames per second using a Dell Dimension 8250 computer equipped with a GeForce Ti 4200 graphics card displayed on a DA-LITE screen using a Sharp Notevision 6 projector. The projected image size was 109.22 centimeters (width) by 147.32 centimeters (height) and participants sat approximately 5.28 meters away from the screen creating a viewing angle of 15.8°.

Testing Phase. Spatial knowledge was assessed in different modes from learning (transfer test measures) using immersive VR for spatial updating and map construction task. Pointing error (spatial updating) was measured using a Virtual Research V8 HMD, which had an immersive view displaying the same virtual city from a first-person perspective using Alice99. The VE was displayed in the HMD using stereo images rendered at 640 by 480 and 60 frames per second with a horizontal field of view of 48°. A Dell Precision 360 computer equipped with a GeForce 4 MX420 and GeForce 4 MX200 was used to render the virtual city for the HMD. Head movements were registered to update the images seen through the HMD using an Intersense IS-900 motion tracking system. Participants rotated in place and used a tracked wand to point at target locations that were out of sight, shown in Figure 4.

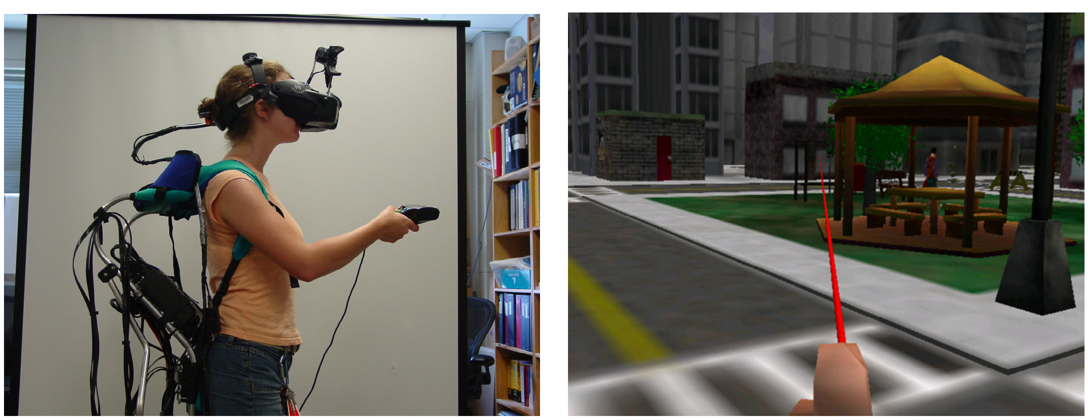

Figure 4. Head-mounted virtual reality holding the wand (left). View of the environment seen through the head-mount with the hand-held wand acting as a pointer (right).

Angular pointing error was measured as a function of the deviation of the center of mass from the target being pointed to, ignoring elevation. Higher pointing error is less accurate spatial updating performance; see Figure 5 for a hypothetical example of pointing error. Pointing accuracy was assessed from the angle formed between a perfect pointing response and the actual pointing response.

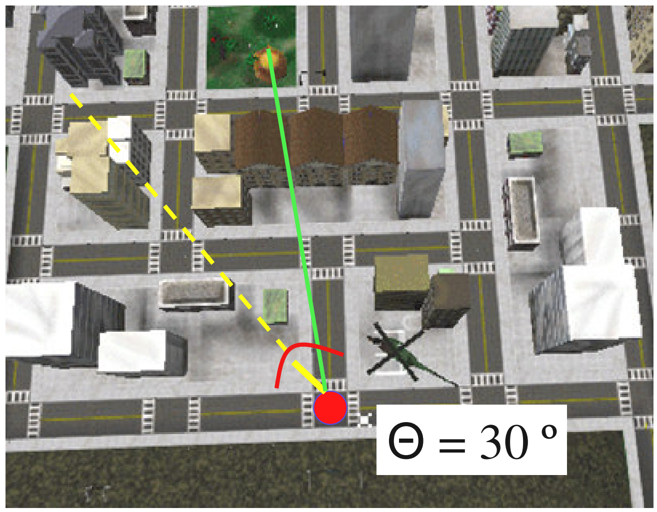

Figure 5. Hypothetical example of pointing error from above. This view was never seen by participants. The red dot represents the standing location at the helicopter. A perfect pointing response (0°) to the gazebo is shown with the green line. The yellow dotted line shows a pointing error of 30°.

Next, participants used a program to place target locations on a blank map displayed on a NEC 1500M flat panel display (38 cm diagonal). The map program recorded the locations of target placements in pixel coordinates (x, y).

Questionnaires. Participants completed two questionnaires on video game experience and navigation abilities. These two measures were assessed because individual differences in video game experience (Darken & Peterson, 2002) and navigation abilities (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002) are associated with acquiring spatial knowledge in VEs. See Appendix A for the video game experience questions. An example question is “Average number of hours per week spent playing first person video games[5]?" Navigation abilities were measured using the Santa Barbara Sense of Direction Questionnaire (SBSOD) (Hegarty et al., 2002). An example question is "I very easily get lost in a new city?" with responses on a seven point Likert scale ranging from "strongly agree" to "strongly disagree."

Design and Procedure

There were three conditions in this study:

1) Active: coupled spatial decision-making and control.

2) Decider: only spatial decision-making (i.e. "backseat driver"), participants instructed the experimenter where to go.

3) Controller: participants only had joystick control, the experimenter instructed participants where to go based on the trajectories from matched decider participants.

This experiment used a between-participants design. Participants were randomly assigned to a learning condition, with the constraint of creating matched pairs between decider and controller participants to ensure they had comparable visual experience during learning. The focus of Experiment 1 was to disentangle the components of active navigation, not to elucidate the comparisons between active navigation and passive navigation. Hence, no passive learning condition was presented. Each condition had twenty participants and an approximately equal number of male and female participants: active condition (9 male, 11 female), decider condition (10 male, 10 female), and controller condition (11 male, 9 female).

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[5] First person video games are action games. As the name suggests, the perspective is egocentric and typically involves rapid movement and actions (e.g. shooting) through a computer generated environment.

For the learning phase, the starting target location was randomized, except for the controller condition, which was matched to the decider condition. During the testing phase, the order of targets to be pointed to was randomized. Since constantly jumping around to different target locations after each trial would be disconcerting, the randomization was conditional on having all of the pointing responses for each occur consecutively.

Experiment Instructions. Participants were told to find and learn the locations of the five targets in the virtual city environment and that they would have 20 minutes to do so. Pictures and names of five target locations were placed in the table in front of participants. Next, participants were *explicitly* instructed that their knowledge of the virtual city would be assessed by having them stand at target locations and pointing at the ones that were out of sight. The real-world example of spatial updating provided to participants was pointing at The Rotunda (a salient, well-known landmark at the University of Virginia), which was not visible from the experiment room. Last, participants were told they would create a top-down map of the five target locations. The experiment took approximately one hour to complete.

Practice Phase: Active Condition. First, participants were instructed on using the joystick and then they practiced moving for one to two minutes. They practiced in a VE created for this purpose. Control proficiency was ascertained by having participants travel around a city block in the practice VE in under 45 seconds. Two participants needed extra practice to attain control proficiency, but were able to pass the criterion on their second attempt.

Practice Phase: Controller and Decider Conditions. In the controller condition, the procedure was the same as the active condition with one addition. The experimenter gave verbal directions (e.g. turn left at the next intersection) in the practice VE to ensure the participant would understand the instructions. Contrary to the other two conditions, participants in the decider condition did not receive any training or practice with the joystick controls. However, they did receive a brief training session giving the experimenter verbal directions about where to go in the practice VE (e.g. keep going straight, stop and turn around).

Learning Phase. For the active and decider conditions, 20 minutes were given to free-explore the virtual city and participants were told to use whatever strategy they wanted to learn the locations of the five targets keeping in mind the test that would follow learning. Controllers also traversed the VE for 20 minutes, but did so following the verbal directions from the experimenter. The 20 minute learning time was sufficient for all active and controller participants to visit every target location at least once.

Testing Phase. For all learning conditions, the same procedures were used for assessing the two measures of spatial knowledge (pointing error and map construction). Pointing error was assessed using HMD VR. Participants stood at each of the five target locations and pointed to the other four unseen locations using the wand. For pointing, participants were asked to imagine that the virtual pointer that extended from the end of the wand would go straight through buildings and other objects to directly hit the target they were pointing at. Pointing responses were indicated by pressing a button on the bottom of the wand which also changed the color of the virtual pointer. Participants were asked to hold the wand steady and quickly click the button for pointing. However, if there was more than a 2° disparity between the button press and button release the pointing response was repeated. For the map task, participants placed the five target locations on the blank map displayed on a computer screen. They were further instructed that the orientation and scale of the constructed map did not matter. The example of orientation invariance and scale invariance offered to participants was a map that one can rotate around and zoom in and out on.

Results

Learning in the active and decider conditions lead to comparable pointing error and map construction accuracy, whereas controllers had higher pointing error and constructed less accurate maps. The results match the hypotheses that having the ability to make decisions about where to go, not control, is the critical component for learning the spatial layout of a virtual environment.

Pointing Error. Angular pointing error was analyzed by taking the absolute value, which provides an overall measure of spatial updating accuracy. The average absolute values of the four pointing responses per standing target location were computed for each participant (e.g. standing at the gazebo and pointing at each of the other four targets). Pointing error was analyzed using planned contrasts with a repeated measures ANOVA, with 5 (average absolute pointing error for each target stood at) specified as a within-participants factor and 3 (condition) specified as a between-participants factor.

As hypothesized, the active and decider conditions had lower pointing error than the controller condition, $t(57) = 2.58$, $p < .001$, $d = .81$. A second planned contrast indicated that the active and decider conditions were not statistically different, $t(57) = .21$, $p = .83$, $d = .07$. Results are shown below in Figure 6.

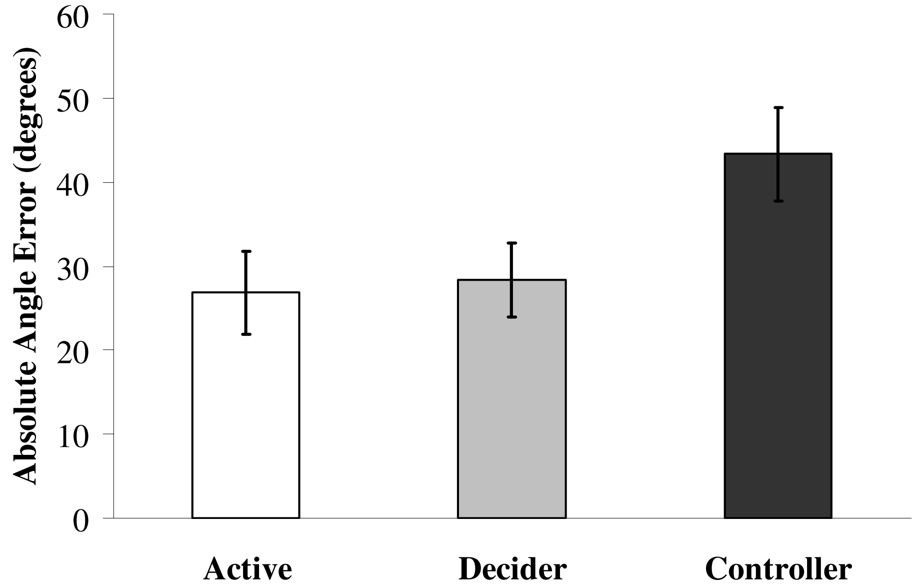

Figure 6. Mean values of absolute pointing error in degrees by condition. Lower pointing error indicates a more accurate response. Error bars represent one standard error of the mean.

The ANOVA indicated a main effect of target standing location, $F(4, 228) = 10.67$, $p < .001$, $\eta_p^2 = .16$, indicating that the accuracy of pointing responses varied by the location at which participants stood. There was no standing location by condition interaction, $F(2, 57) = .60$, $p = .55$, $\eta_p^2 = .02$.

Since pointing error is angular, it is a cyclical measure that can be further evaluated with unit vectors using circular statistics (Batschelet, 1981; Fisher, 1953). Circular statistics can be used to determine types of pointing errors potentially masked by taking absolute values. Two types of angular error can be calculated using circular statistics:

1) Constant error: systematic directional bias.
2) Variable error: deviations independent of systematic bias.

There was a high positive correlation between the absolute pointing error and variable pointing error, $r(58) = .94$, $p < .001$, two-tailed. The large correlation between absolute error and variable error implies constant error at the group level is around zero (Schutz & Roy, 1973). The absence of a systematic bias in pointing error indicates that there was no common pattern of constant error in pointing responses. Therefore, only absolute error is presented.

Map Construction. Map construction accuracy was assessed using a bidimensional regression (BDR) (Friedman & Kohler, 2003; Tobler, 1994). BDR fits a solution between two sets of (x, y) coordinates that minimizes the difference. This analysis is invariant for both scale and rotation, yielding a measure of similarity, *r* (the BDR equivalent of a correlation coefficient), between the map created by each participant and the actual configuration of target locations. A graphical depiction of BDR is shown in Figure 7.

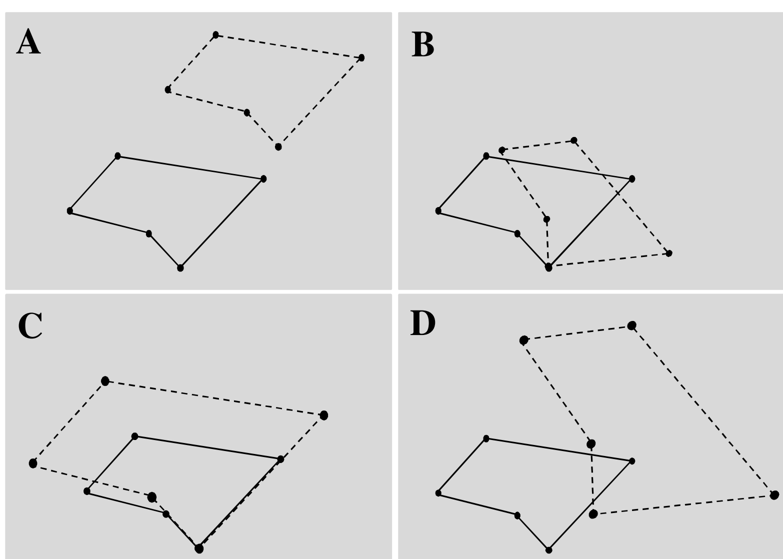

Figure 7. All panels show the actual configuration shape of targets. Lines represent Euclidean distances between target locations. Shapes with solid black lines are the actual configuration of target locations and shapes with dotted lines represent created example configurations. These illustrations show the configural translation, rotation, and scale

invariance of bidimensional regression and are based Figure 1 in Friedman and Kohler (2003), p. 470. All created configurations have a perfect bidimensional regression fit to the actual configuration ($r = 1.00$). A: translation, B: 41° clockwise rotation, C: 60% increase in scale, and D: translation, 41° clockwise rotation, and 60% increase in scale.

The supplemental materials from Friedman & Kohler (2003) were used to compute a four parameter Euclidean BDR for each participant. The distribution of the *r* values was negatively skewed so a Fisher r-to-z transformation was applied to make the data more normal.

Like pointing error, analyses for the map data were performed using planned contrasts. As hypothesized, participants in the active condition and decider condition constructed more accurate maps than those in the controller condition, $t(57) = 3.53$, $p < .001$, $d = 1.12$. A second planned contrast indicated the active and decider conditions were statistically equivalent, $t(57) = .19$, $p = .85$, $d = .06$. Results are shown in Figure 8.

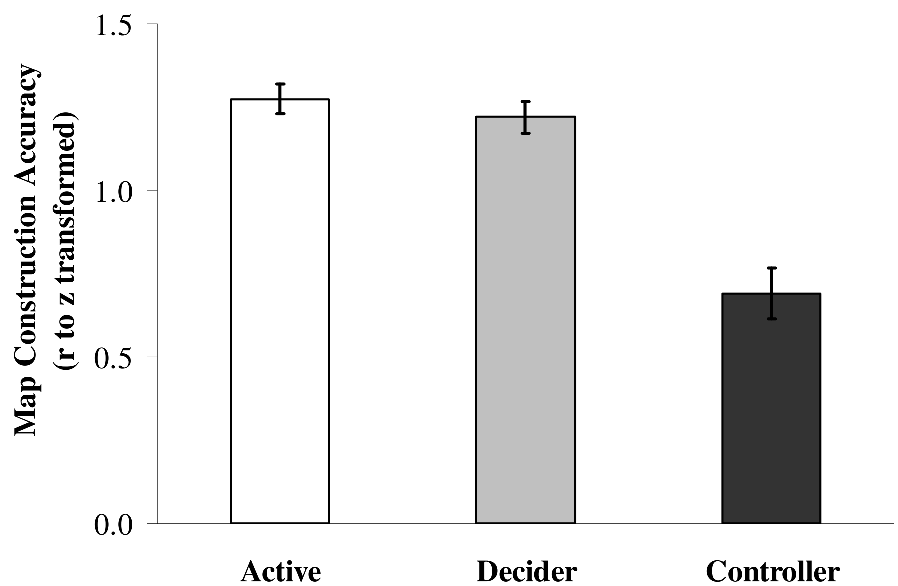

Figure 8. Transformed mean values of bidimensional map construction accuracy by condition. Higher values indicate a closer resemblance to the actual configuration of targets. Error bars represent one standard error of the mean.

Questionnaires

No reliable differences between conditions in either the SBSOD scale or the measures of video game experience were observed. This suggests each condition had participants with comparable levels of self reported navigation ability and video game experience. See Table A1 in Appendix A for descriptive statistics of the self-report data. Both self report measures were analyzed using separate two-way ANOVAs with 3 (condition) by 2 (sex) specified as between-participant factors.

For the SBSOD scale, there was no main effect of condition, $F(2, 53) = .49$, $p = .62$, $\eta_p^2 = .02$, nor was there a main effect of sex, $F(1, 53) = 2.79$, $p = .10$, $\eta_p^2 = .05$. Also, the interaction between condition and sex was not reliable, $F(1, 53) = .46$, $p = .63$, $\eta_p^2 = .02$. One participant did not complete the SBSOD scale.

Since the questions assessing video game experience (experience with first-person shooter games and hours spent playing these games) were strongly correlated, $r(58) = .70$, $p < .001$, two-tailed, a composite video game experience variable was created by averaging z-scores from these two questions. For this composite measure, there was no main effect of condition, $F(2, 54) = .27$, $p = .77$, $\eta_p^2 = .01$.

For video game experience, there was a main effect of sex, $F(2, 54) = 40.72$, $p < .001$, $\eta_p^2 = .43$. Males ($M = 1.09$, $SE = .32$) had higher levels of video game experience than females ($M = -1.16$, $SE = .13$). No condition by sex interaction was found, $F(2, 54) = 4.03$, $p =.12$, $\eta_p^2 = .08$.

Correlations

Correlations between the two dependent measures of spatial knowledge and two self-report measures were also analyzed; see Table 1B in Appendix B. There was a large negative association, $r = -.68$, between pointing error and map construction accuracy (more accurate, lower, pointing error was correlated with higher map construction accuracy). However, the dependent measures have been postulated to assess different levels of spatial knowledge (Kitchin & Blades, 2002) and, while measures of spatial knowledge are related, they are also partially dissociable (Allen et al., 1996).

Other significant correlations include moderate associations between most of the self-report measures and the dependent measures of spatial knowledge. These associations are consistent with validity of the SBSOD (Hegarty et al., 2002) and the postulated positive link between action video game experience and spatial knowledge for VEs (Darken & Peterson, 2002).

Sex Differences

Pointing error and map construction accuracy were also analyzed for sex differences, although no specific pattern was hypothesized. These analyses were performed using two-way ANOVAs with 3 (condition) by 2 (sex) specified as between-participant factors. For pointing error, the main effect of sex was significant, $F(1, 54) = 33.09$, $p < .001$, $\eta_p^2 = .38$, males had more accurate pointing responses ($M = 19.67°$, $SE = 3.33°$) than females ($M = 46.93°$, $SE = 3.55°$). No interaction was observed between sex and condition, $F(2, 54) = .03$, $p = .97$, $\eta_p^2 = .001$. For the map task, there was a main effect of sex, $F(1, 54) = 15.31$, $p < .001$, $\eta_p^2 = .22$, with males constructing more accurate maps (transformed r-to-z = 1.38, transformed $SE = .05$) than females (transformed r-to-z = .76, transformed $SE = .04$). No interaction between condition and sex was observed, $F(2, 54) = .10$, $p = .91$, $\eta_p^2 = .004$.

Discussion

These results show that spatial decision-making alone, the ability to chose where to go, facilitates the acquisition of spatial knowledge. It is unlikely these effects can be attributed anything but the experimental manipulation. Visual experience between the decider and controller conditions was comparable because they traversed the same paths. Since the active navigation condition had coupled spatial decision-making and control, the paths participants chose to take were different from the other two conditions. However, as hypothesized, spatial knowledge for active learning was equivalent to spatial decision-making and both were more accurate than navigation with only control. It is improbable that decreased attention for controllers can explain the results because the instructions explicitly specified how spatial knowledge would be assessed. Furthermore, these results cannot be explained by individual differences in control proficiency, navigation ability, or video game experience. Therefore, the deficiency in spatial knowledge for guided navigation is caused by the absence of being able to decide where to go.

2.4 Experiment 2: Augmenting Guided Navigation with Visual Aids

Experiment 2 investigated the use of visual aids (dynamic signpost and beacon landmarks) for ameliorating the loss of spatial knowledge under guided navigation. Navigation was guided by simple voice commands for turn directions (e.g. “Turn right”). Spatial knowledge was assessed by having participants reproduce routes between targets that had been learned under guidance, without any aids or guidance available. This measure was selected, instead of the spatial updating used in Experiment 1, in order to ascertain navigation performance more directly. The same map construction task was used again.

Method

Participants

Forty-two (21 male, 21 female mean age = 18.55) University of Virginia students participated in this experiment for course credit. Two participants were excluded from taking part in the study because using the joystick was uncomfortable (one had a broken wrist and the other had a broken finger, both on the dominant hand). These two participants were replaced.

Equipment

The same virtual city as Experiment 1 was used. However, it was learned on a three projector display (Infocockpit) as opposed to the large projected display used earlier. Unpublished data indicates the accuracy of spatial knowledge is similar between the display used in Experiment 1 and the Infocockpit (three large projected screens) used in Experiments 2 and 3. Figure 9 shows the large projected screens of the Infocockpit.

Figure 9. The Infocockpit with a 110° field of view and three projected displays.

Practice and Learning Phases. Like Experiment 1, participants used a Saitek Cyborg EVO joystick to control their movement. The VE was rendered at 640 by 480 and 15 frames per second using an Appian Rushmore four port video card on a Dell Precision 530MT computer. The Infocockpit consisted of three InFocus LP650 projectors and a curved screen. The dimensions of the screen, measured flat, are 140.25 cm tall, 229.5 cm wide, and 285.6 cm diagonally. Participants sat 1.58 m away from the screen. To reduce distortion near the edges of the curved screen, the images displayed by the left and right projector were slightly cropped. The Infocockpit condition subtended a viewing angle of 100°, providing substantial peripheral visual information about the city environment.

During learning, two speakers were used to play back the auditory guidance monaurally. The auditory guidance was about 1 to 1.5 seconds in length and was activated 3 to 4 seconds prior to reaching an intersection (decision point) in order to give participants time to follow the instructions. Guidance consisted of “Keep straight”, “Turn right”, “Turn left”, and “Stop at X”, where X was the final target location.

The dynamic signpost and beacon aid were both present when the virtual city was learned with visual aids, shown in Figure 2 above. The colors for the aids, which corresponded to each target, were approximately yellow for the tank, red for the school, gray for the helicopter, green for the humvee, and orange for the gazebo. The dynamic signpost had arrows with these colors, which pointed at the appropriate targets in real-time with rotations. Length of the arrow corresponded to Euclidean distance to the target. Also, a small picture of the target was displayed at the end of each arrow. The beacon aid also used the same color scheme with arrows, except they were vertically oriented, and the size of these arrows scaled with viewing distance. From far viewing distances, the top of the beacon, which showed a 2d picture of the target, was visible.

Testing Phase and Questionnaires. In contrast to the transfer test measure of spatial updating in Experiment 1, here spatial knowledge was assessed by having participants replicate the same route they had taken during learning and a novel route using the Infocockpit. Trajectory data was recorded to score route accuracy. The visual aids were always turned off at test. Like Experiment 1, the same map task was performed, but on a Dell 1900FP flat panel display (48.45 cm diagonal). The same two questionnaires used in Experiment 1, video game experience and the SBSOD scale, were administered in Experiment 2.

Design and Procedure

The virtual city was always learned under auditory guidance with visual aids or without visual aids using a between-participants design. There were two unique route sequences between pairs of target locations (helicopter-gazebo-school-humvee-tank or tank-humvee-school-gazebo-helicopter), see Figure 10.

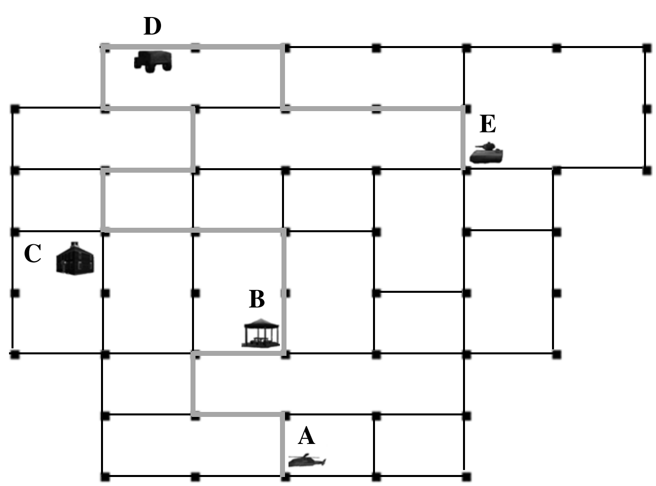

Figure 10. Top down drawing of the virtual city. The black squares represent intersection and the black lines depict streets. The five targets are labeled by letters (A: helicopter, B:

gazebo, C: school, D: humvee, and E: tank). The gray lines show the routes learned, either in alphabetical order or reverse alphabetical order, under guidance.

Participants were randomly assigned to a learning condition (visual aids or no aids) and route sequence. Each learning condition had twenty participants and an approximately equal number of male and female participants: guided navigation with aids (11 male, 9 female) and guided navigation without aids (10 male, 10 female).

Experiment Instructions. Participants were *explicitly* instructed that their knowledge of the virtual city would be assessed via reproducing the same routes they would learn and by creating a top-down map of the five target locations. They were also told they would follow auditory guidance during learning, but no guidance (or aids if applicable) would be available when they were tested. The experiment took about 30 minutes to complete.

Practice Phase. The same procedure and practice environment as Experiment 1 were used here. A single participant needed extra practice to reach the criterion, reaching it on the second attempt. Also, participants were shown that the last auditory guidance message could be played again by pressing the trigger on the joystick.

Learning Phase. Similar to Experiment 1, pictures of the five target locations were placed in front of participants and ordered from left to right to match the sequence that would be taken during learning. In the visual aids condition, participants were shown how the dynamic signpost represented information (arrow length for target distance and arrow orientation for the direction of the target with respect to current heading). They were also shown the arrow indicators of the beacon aid. The instructions with visual aids added about 30 seconds of time in the environment relative to the unaided condition, but no exploration was occurring.

Testing Phase and Questionnaires. The assessment of route replication always matched the order of learning. If participants traversed three additional intersections (the distance between each intersection, is a segment, representing a city block) longer than the optimal route length they were "warped" which took them directly to the destination. The constraint of three additional segments was imposed to minimize the possibility of learning at test. Finally, participants were instructed to take the shortest path, starting at last target during to the first target during learning. Taking the shortest path between these locations was never directly experienced at learning, making it novel.

Results

The visual aids improved spatial knowledge for route replication, but not for the two measures of survey knowledge (novel route execution and the map task).

Route Accuracy Score. To score the accuracy of routes with greater precision than a dichotomous correct/incorrect value, a metric was created by weighted the distance traveled at test by the optimal route length. The formula is:

$Score = 100\% - \frac{1}{(L+3)} \times (A + D) \times 100\%$, where *L* = optimal number of route intersection including the start, *A* = number of additional intersections beyond optimal, and *D* = number of intersections away from target or one if the route length is the same at learning, but a different path. Note, in order to set the lower bound at 0%, $D \le L$ (i.e. the maximum penalty is the optimal number of segment to the destination). The denominator contains the number three because the maximum route length was constrained to the optimal number of intersections (*L*) plus three intersections. The route accuracy values are in Appendix C. Note, the route accuracy measures accounts for distance, but does not weight intersection complexity (e.g. three-way intersection, four-way intersection, etc) in route scoring.

Route Replication. The route replication measure was analyzed with planned contrasts using a repeated measures ANOVA with 4 (routes between targets) specified as a within participants factor and 2 (condition) specified as a between participants factor. As hypothesized, the planned contrast, collapsed across the four routes, showed the guidance condition with visual aids had higher route accuracy than the unaided guidance condition, $t(38) = 2.36$, $p = .01$, $d = .75$, see Figure 11. Practically, this difference approximated to a 20% increase in travel distances for learning without aids.

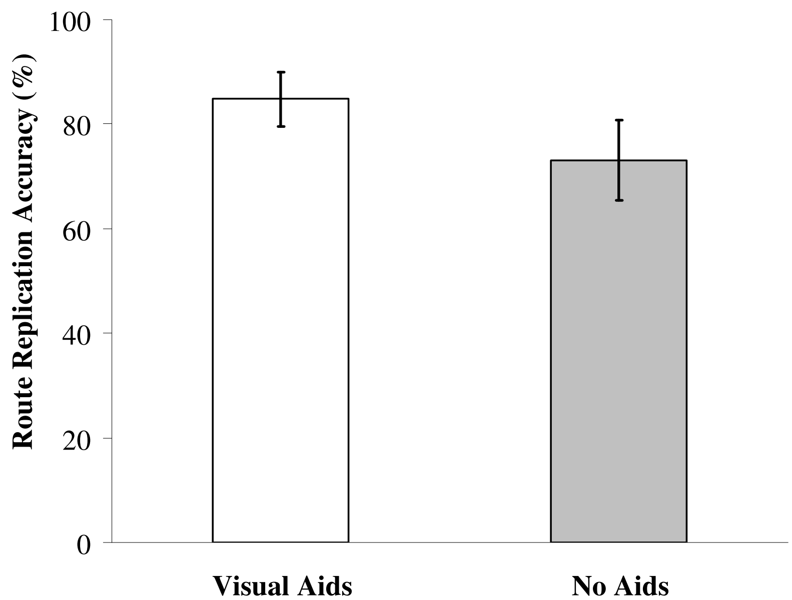

Figure 11. Mean values of route replication accuracy by condition, collapsed across routes. Error bars represent one standard error of the mean.

The ANOVA indicated a marginal main effect of route type, $F(3, 114) = 2.44$, $p = .07$, $\eta_p^2 = .06$, suggesting fairly small performance variations between routes. There was no route by condition interaction, $F(3, 114) = .02$, $p = 1.00$, $\eta_p^2 < .001$.

Novel Route Execution. The last route participants executed was a novel route because it involved traversing a path that was not directly experienced at learning. This entailed taking the shortest route from the last target reached during learning to the starting target. The survey route measure was analyzed with a planned contrast using a one-way ANOVA, with condition specified as a between-participants factor. There was no significant difference in accuracy for executing the novel route between visual aids (M = 85.91%, SE = 4.50) and no aids (M = 78.64%, SE = 6.30), $t(37) = .47$, $p = .32$, $d = .15$ (planned contrast). Although the mean difference is in the hypothesized direction, the result is neither statistically significant nor meaningful given the small effect size. One participant had a novel route execution score more than three standard deviations below the mean and was therefore excluded from the analyses.

Map Construction. A measurement of map construction accuracy was created using bidimensional regressions. The bidimensional regression coefficients were then analyzed with a planned contrast using a one-way ANOVA, with condition specified as a between-participants factor. The distribution of the coefficient was negatively skewed, so Fisher r-to-z transformation was performed to make the data more normal. Contrary to the hypothesis, the planned contrast showed there was no reliable difference between the guidance condition with visual aids (transformed r-to-z M = 1.84, transformed SE = .13) and the guidance condition without aids (transformed r-to-z M = 1.66, transformed SE = .18), $t(38) = .84$, $p = .20$, $d = .27$. Like the novel route measure, the mean difference is in the hypothesized direction, but the effect size is quite small.

Questionnaires

No differences between conditions were observed for the SBSOD scale or videogame experience. See Table A1 in Appendix A for descriptive statistics of the self-report data. Both self report measures were analyzed using separate two-way ANOVAs with 2 (learning condition) by 2 (sex) specified as between-participant factors.

For the SBSOD scale, there was no main effect of condition, $F(1, 36) = 12.48$, $p = .84$, $\eta_p^2 < .01$, but there was a main effect of sex, $F(1, 36) = 18.24$, $p < .001$, $\eta_p^2 = 33$, males ($M = 73.90$, $SE = 2.72$) and females ($M = 54.47$, $SE = 3.64$). The condition by sex interaction was not reliable, $F(1, 36) = .86$, $p = .36$, $\eta_p^2 = .02$.

Since the questions assessing video game experience (experience with first-person shooter games and hours spent playing these games) were strongly correlated, $r(38) = .66$, $p < .001$, two-tailed, a composite video game experience variable was created by averaging z-scores from these two questions. For the composite measure, there was no main effect of condition, $F(1, 36) = .004$, $p = .95$, $\eta_p^2 < .001$. There was a main effect of sex, $F(1, 36) = 21.54$, $p < .001$, $\eta_p^2 = .37$, with males ($M = .52$, $SE = .17$) demonstrating higher levels of video game experience than females ($M = -.57$, $SE = .16$). No condition by sex interaction was found, $F(1, 36) = 1.39$, $p = .25$, $\eta_p^2 = .04$.

Correlations

Correlations between the dependent measures and two self-report measures were analyzed; see Table 2 in Appendix B. Route replication and map construction accuracy were positively related, $r = .42$, $p = .007$. There was also a trend towards a positive association between route replication and the novel route execution measure, $r = .30$, $p = .07$. However, the dependent measures have been postulated to assess different levels of spatial knowledge (Kitchin & Blades, 2002) and other work has shown partial dissociations between measures of spatial knowledge which are consistent the conceptual

LRS model (Allen et al., 1996).

Route Learning Sequence

Since there were two different route sequences for learning the environments, additional analyses were conducted to ascertain if differences, or lack thereof, could be attributable to learning sequence. This analysis was conducted by adding learning sequence as a between-participants factor to the ANOVAs for route replication, novel route, and the map task. Route learning sequence was not significant for the three measures; route replication, $F(1, 36) = .37$, $p = .55$, $\eta_p^2 = .01$, novel route, $F(1, 35) = .30$, $p = .59$, $\eta_p^2 = .008$, and map task, $F(1, 36) = 2.19$, $p = .15$, $\eta_p^2 = .06$ Lastly, the interactions (learning condition x route learning sequence) for each ANOVA were not significant, $p = .99$ and $\eta_p^2 < .001$ (route replication), $p = .33$ and $\eta_p^2 = .02$ (novel route), and $p = .41$ and $\eta_p^2 = .02$ (map task).

Sex Differences

No pattern of sex differences was hypothesized. Sex differences were analyzed by including it as a between-participants factor in the ANOVAs for the three measures of spatial knowledge. There were no sex differences for two measures; route replication, $F(1, 36) = 1.06$, $p = .31$, $\eta_p^2 = .03$ and novel route execution, $F(1, 35) = 1.25$, $p = .27$, $\eta_p^2 = .04$. However, males constructed more accurate maps (transformed r-to-z $M = 2.00$, transformed $SE = .13$) than females (transformed r-to-z $M = 1.48$, transformed $SE = .15$), $F(1, 36) = 6.52$, $p = .02$, $\eta_p^2 = .15$. Lastly, the interactions (condition by sex) for each ANOVA were not significant, $p = .42$ and $\eta_p^2 = .02$ (route replication), $p = .32$ and $\eta_p^2 = .03$ (novel route execution), and $p = .34$ and $\eta_p^2 = .03$ (map construction accuracy).

Discussion

These results show that visual aids were only effective in improving spatial knowledge for reproducing learned routes. For the other two measures, the directions of the means match the hypotheses, but the effects were quite small. There are several possible reasons. First, the visual aids may simply not be effective for improving accuracy for novel route execution and creating a map. Second, because route replication was always the first dependent measure it is possible that additional encoding of spatial relations occurred while it was being performed and boosted performance on the other two measures. However, results from Experiment 3 indicate this possibility is unlikely, as does the high accuracy for the route replication measure. Third, the presence of a ceiling effect for all measures could have reduced the sensitivity to detect differences. Consistent with Experiment 1, it is doubtful that the results can be explained by individual differences in potentially relevant variables (control proficiency, navigation ability, or video game experience).

2.5 Experiment 3: Augmenting Guided Navigation with Spatialized Sound

In Experiment 3, guided navigation was augmented by using the auditory turn instructions as an aid. This was done by adding cardinal directions to the guidance and spatializing the sound to correspond to the virtual city (e.g. "Turn right, heading north" was heard in the right ear). Cardinal directions are often ignored because they are confusing; this aid was hypothesized to make it easier to understand the virtual city in environmental coordinates ("north" is invariant to heading direction, but "left" is viewer-centered), thus improving the accuracy of spatial knowledge for guided navigation. There were two other conditions, monaural auditory guidance with cardinal directions and monaural egocentric guidance. The egocentric guidance was not spatialized because directions like left and right are dependent on viewpoint, unlikely to be beneficial integrating of environmental relations. Spatial knowledge was assessed using the same measures as Experiment 2 and without any guidance available.

Participants

Sixty (32 male, 28 female, mean age = 18.62) University of Virginia students participated in this experiment for course credit.

Equipment

The same equipment as Experiment 2 was used. Instead of visual aids, the auditory guidance was augmented. For the stereo cardinal direction guidance, the auditory instructions were augmented by using stereo sound to match the specified directional heading to the environment. For example, “Turn right, heading north” was heard in the right ear. For monaural cardinal guidance, verbal instructions were played back through both speakers. Instructions containing cardinal direction were 2 to 3 second in length. The monaural egocentric guidance instructions were like the unaided condition in Experiment 2, e.g. “Turn right”.

Design and Procedure

All aspects of the design and procedure are identical to Experiment 2, except the aid was auditory guidance. Participants were randomly assigned to one of three learning conditions (stereo cardinal guidance, monaural cardinal guidance, or monaural egocentric guidance). Also, participants were given the same explicit instructions, but contrary to Experiment 2 no information about the aid was explained, because prior work has shown spatialized audio in guidance is used automatically (Klatzky et al., 2006). Each condition had twenty participants and an approximately equal number of male and female participants: stereo cardinal directions (10 male, 10 female), monaural cardinal guidance (9 male, 11 female), and egocentric guidance (13 male, 7 female).

Results

The hypotheses were not supported. Only the novel route execution measure was influenced by augmentation. Stereo cardinal guidance and monaural cardinal guidance led to comparable accuracy for novel route execution and both were more accurate than monaural egocentric guidance. Last, there were no accuracy differences between the types of guidance for replicating learned routes and constructing maps.

Route Replication. Routes were scored using the same metrics as Experiment 2. The route replication measure was analyzed with a planned contrast and using a repeated measures ANOVA with 4 (routes between targets) specified as a within participants factor and 3 (condition) specified as a between participants factor. Contrary to the hypothesis, the planned contrast, collapsed across the four routes, showed there was no advantage for stereo cardinal guidance (M = 86.42%, SE = 2.27) over monaural cardinal guidance (M = 81.40%, SE = 4.29) and egocentric guidance (M = 85.58%, SE = 2.52), $t(57) = .76$, $p = .23$, $d = .21$. The ANOVA indicated no main effect of condition, $F(2, 57) = .72$, $p = .49$, $\eta_p^2 = .03$. There was a small, but significant main effect of route type, $F(3, 171) = 4.51$, $p = .005$, $\eta_p^2 = .07$, indicating small variations in completion accuracy between routes. The route by condition interaction was not significant, $F(6, 171) = .39$, $p = .89$, $\eta_p^2 = .01$.

Novel Route Execution. The novel route measure was first analyzed using a planned contrast which was not significant. Therefore, the subsequent analyses used a one-way ANOVA with condition specified as a between-participants factor and followed by post-hoc tests. The planned contrast indicated that novel route performance was not higher for stereo cardinal compared to the other two conditions, $t(57) = 1.20$, $p = .12$, $d = .33$ (planned contrast). The one-way ANOVA indicated a main effect of condition, $F(2, 57) = 4.07$, $p = .02$, $\eta_p^2 = .13$. Using Tukey's HSD, post-hoc tests revealed no difference between stereo cardinal and monaural cardinal, $p = .97$, $d = .06$, a marginally significant difference between stereo cardinal and monaural egocentric, $p = .06$, $d = .52$, and a significant difference between monaural cardinal and monaural egocentric, $p = .03$, $d = .58$, see Figure 12. In terms of travel distance, novel routes executed for learning with egocentric guidance were approximately 25% longer in length than learning with both types of cardinal directions.

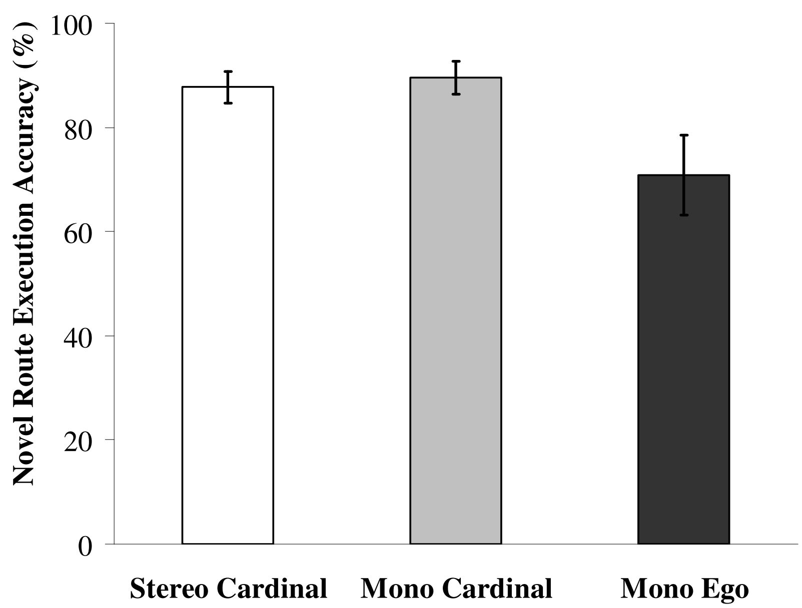

Figure 12. Mean values of novel route execution accuracy by condition. Error bars represent one standard error of the mean.

Map Construction. Map construction accuracy was analyzed with a planned contrast using a one-way ANOVA, with condition specified as a between-participants factor. The distribution of the dependent variable, the bidimensional regression coefficient *r*, was negatively skewed. Therefore, a Fisher r-to-z transformation was applied to make the data more normal. Analyses with planned contrasts yielded conflicting results, matching some hypotheses, but not others. Thus, instead an ANOVA was performed, $F(2, 57) = 1.58$, $p = .22$, $\eta_p^2 = .05$. No main effect of condition was found, stereo cardinal (transformed r-to-z $M = 1.87$, transformed $SE = .13$), monaural cardinal guidance (transformed r-to-z $M = 1.65$, transformed $SE = .13$), and egocentric guidance (transformed r-to-z $M = 1.65$, transformed $SE = .13$).

Questionnaires

No difference between conditions was observed for the SBSOD scale or videogame experience. See Table A1 in Appendix A for descriptive statistics of the self-report data. Both self report measures were analyzed using separate two-way ANOVAs with 3 (condition) by 2 (sex) specified as between-participant factors.

For the SBSOD scale, there was no main effect of condition, $F(1, 54) = .15$, $p = .86$, $\eta_p^2 = .006$, and no main effect of sex, $F(1, 36) = .87$, $p = .36$, $\eta_p^2 = 02$. The condition x sex interaction was not reliable, $F(2, 54) = .75$, $p = .48$, $\eta_p^2 = .03$.

The questions assessing video game experience (experience with first-person shooter games and hours spent playing these games) were moderately correlated, $r(57) = .44$, $p < .001$, two-tailed. This correlation was not as strong as the previous two experiments because all of the female participants reported spending zero hours per week playing video games. The composite video game experience variable was created by averaging z-scores from these two questions. For the composite measure, there was no main effect of condition, $F(2, 53) = 1.72$, $p = .19$, $\eta_p^2 = .06$. There was a main effect of sex, $F(1, 53) = 54.48$, $p < .001$, $\eta_p^2 = .46$, males ($M = .52$, $SE = .16$) had higher levels of video game experience than females ($M = -.58$, $SE = .06$). No condition by sex interaction was found, $F(1, 36) = 2.09$, $p = .13$, $\eta_p^2 = .07$. One participant did not answer the two videogame experience questions and was therefore not included in these analyses or the correlations.

Correlations

Correlations between the dependent measures and two self-report measures were analyzed; see Table 3 in Appendix B. Route replication and map construction accuracy were positively related, $r = .33$, $p < .02$. In addition, novel route execution and map construction were positively correlated, $r = .30$, $p = .02$. For the same reasons as the previous experiments, the measures of spatial knowledge were again analyzed separately.

Route Learning Sequence

Analyses of route learning sequence were conducting by adding it as a between-participants factor to the ANOVAs for route replication, novel route, and the map task. The route learning sequence was not significant for the three measures; route replication, $F(1, 54) = .19$, $p = .67$, $\eta_p^2 = .001$, novel route $F(1, 54) = .55$, $p = .46$, $\eta_p^2 = .01$, and map construction accuracy, $F(1, 54) = .27$, $p = .61$, $\eta_p^2 < .001$ Lastly, the interactions (learning condition x route learning sequence) for each ANOVA were not significant, $p = .83$ and $\eta_p^2 < .001$ (route replication), $p = .07$ and $\eta_p^2 = .10$ (novel route), and $p = .28$ and $\eta_p^2 = .05$ (map task).

Sex Differences

No pattern of sex differences was hypothesized. Sex differences were analyzed by including it as a between-participants factor in the ANOVAs for the three measures of spatial knowledge. There were no sex differences for any of the measures of spatial knowledge; route replication, $F(1, 54) = 1.76$, $p = .19$, $\eta_p^2 = .03$, novel route execution, $F(1, 54) = .56$, $p = .46$, $\eta_p^2 = .01$, and map construction, $F(1, 54) = 2.45$, $p = .20$, $\eta_p^2 = .04$. Lastly, the interactions (condition x sex) for each ANOVA were not significant, $p = .14$ and $\eta_p^2 = .07$ (route replication), $p = .32$ and $\eta_p^2 = .03$ (novel route execution), and $p = .84$ and $\eta_p^2 = .006$ (map task).

Discussion

Contrary to hypotheses, none of the measures of spatial knowledge were effectively augmented with the stereo cardinal directions alone. Although not hypothesized, both stereo cardinal guidance and monaural cardinal guidance resulted in greater accuracy for executing novel routes. There were no differences in route reproduction accuracy or map construction accuracy for any of the learning conditions. While the applicability of a particular measure of spatial knowledge depends on the specific goal or goal(s) in navigation, the most common goal tends to be route travel from an origin to a destination. Nevertheless, finding a new, alternative route for travel to a destination has practical value (e.g. the learned route is blocked requiring a detour) and accuracy for finding novel routes improved with stereo and monaural cardinal guidance.

In contrast, the visual aids in Experiment 2 only reduced the loss of spatial knowledge for reproducing routes. However, the findings in Experiment 3 indicate that it is not likely that reproducing routes resulted in a carry-over effect, boosting performance for finding novel routes and constructing maps. Instead, each type of aid has benefits for different, rather than general, aspects of spatial knowledge. Accuracy in Experiments 2 and 3 was high for all measures, suggesting ceiling effects. However, the differential pattern of results between experiments indicates ceiling effects did not completely deplete power to detect effects.

Chapter 3

3.1 General Discussion and Conclusions

The first experiment supports the hypothesis that environmental knowledge is deficient for guided navigation, because making spatial route choices is absent. Subsequent studies, which used aids to augment guided navigation to reduce the loss of spatial knowledge, had mixed results. The visual aids were effective in improving accuracy for reproducing routes (route knowledge), but not for creating maps or executing novel routes (both aspects of survey knowledge). On the other hand, augmenting the auditory guidance with either type of cardinal directions increased the accuracy for novel route execution over monaural egocentric guidance. However, neither audio mode of cardinal directions helped with replicating routes or constructing maps. These results imply that the aids provide specific augmentation for particular measures of spatial knowledge rather than a general increase in the accuracy, which was hypothesized.

Experiment 1 disentangled the components of active navigation, showing that spatial decision-making alone is the critical component for learning an environment. This demonstrated that coupled control and spatial decision-making are not necessary, the latter component itself is sufficient. In addition, those learning with only spatial decision-making alone or control alone had comparable visual experiences. This reduced the likelihood that differences could be due to variations in what was seen in the environment during navigation as a result of travel not being matched. Furthermore, it is unlikely this finding can be attributed to a lack of attention for guided navigation because instruction explicitly specified how environmental knowledge would be assessed.

Experiments 2 and 3 sought to ameliorate the loss of spatial knowledge with guided navigation and were partially successful. The visual aids (Experiment 2) provided information about the directions and distances to targets relative to current position and heading (dynamic signpost) and increased the visibility of targets (beacon). In Experiment 3, the auditory guidance was augmented by adding cardinal directions and spatializing the sound, relating it to headings in the environment, and monaural presentation of cardinal directions.

Each of these types of aid had different specific benefits for ameliorating the loss of spatial knowledge. The visual aids improved route knowledge and the auditory aid improved survey knowledge, creating a map for stereo cardinal directions and finding a novel route for stereo and monaural cardinal directions. In contrast to Experiment 1, there was high accuracy for all measures of spatial knowledge in Experiments 2 and 3. Note, however two of the measures of spatial knowledge, route reproduction and novel route execution, used in Experiments 2 and 3 were different. The lack of significant differences could be because of ceiling effects; however, each experiment with augmentation had a different measure of spatial knowledge with reliable differences. Therefore, it is more plausible that the efficacy of each aid is simply not generalizable to all aspects of spatial knowledge. These explanations are not mutually exclusive. It may be a combination of ceiling effects and weaker effects of aids for certain measures of spatial knowledge relative to other ones.

3.2 Why is Spatial Knowledge Deficient with Guided Navigation?

I claim that the lack of spatial decision-making in guided navigation is the reason why environmental knowledge is less accurate than navigation with spatial choices. This is well supported by the contrasting information for spatial decision-making (environmental relations: where one is, where one is going, and how one is going to get there) and control (actions can performed using online visual information by following heuristics). This interpretation fits with theories in perception and action, including the sufficiency of online visual information for executing actions using control heuristics (Fajen, 2005a). Also, the influences of spatial decision-making on representations of the environments are similar to roles of embodiment and intention to act have on perceiving spatial layout (Proffitt, 2006). In addition, spatial decision-making is interactive with the environment, because there is a reciprocal relationship between choices and integration and updating of spatial relations. Finally, the conceptualization of spatial decision-making matches the descriptive framework proposed by Garling and Golledge (2000) and there are dissociable neural correlates for spatial decision-making and control (Ekstrom et al., 2003; Maguire et al., 1998).

The informational differences between spatial decision-making and control are not directly addressed by current theories in navigation (Shelton & McNamara, 2001, 2004; Waller & Hodgson, 2006). This is for two reasons. First, components of navigation are not included in these theories, making the connection tenuous. Second, the empirical support for these theories are generally based on experiments using small to medium-scale environments, not navigation in large-scale environments like the present work. Environmental scale matters because spatial abilities are not unitary across different size environments; spatial abilities for small-scale and large-scale environments are distinct, but related constructs (Hegarty et al., 2006). Therefore, theories contingent on small-scale spaces may not generalize to large-scale spaces. In addition, the multilevel model of control (Loomis & Beall, 2004), which posits spatial representation of the environment for actions, and of actions capabilities themselves, is incompatible. This is because spatial decision-making and control, as defined here, are clearly dissociable components of navigation. For control alone, online visual information without spatial representation is sufficient for action. Another potential explanation for differences between spatial decision-making and control is the role of attention.

3.3 Attention and Spatial Knowledge

The potential role for attention is mitigated, in all experiments, because the instructions explicitly stated how spatial knowledge would be assessed. Thus, at best, attention is more likely to be a contributing factor than the sole explanation. P. N. Wilson & Péruch (2002) have found a high level of attention (using explicit instructions on assessment of spatial knowledge) nullifies differences in spatial knowledge between learning modes, specifically active versus passive navigation. However, differences in all studies still emerged, despite a high level of attention. Spatial knowledge was less accurate for guided navigation than for navigation where choices were permitted and the aids had some efficacy for improving guided navigation.

Although using explicit instructions does not guarantee attention was allocated similarly across learning modes, it reduces the likelihood that attention is the primary reason for differences. Furthermore, this argument is consistent with the P. N. Wilson & Péruch (2002) contention that explicit instructions result in a high level of attention, independent of learning mode. If anything, the large effects in Experiment 1 would likely be even greater if spatial knowledge had been tested incidentally. Also, in Experiments 2 and 3, spatial knowledge would have likely been less accurate for guided navigation without aids, creating the appearance of more effective augmentation. On the hand, incidental testing of spatial knowledge is more like the real-world use of a navigation system, but effective augmentation would have been attributable to attentional differences. That is, participants learning with aids could simply be paying more attention to the environment than those that did not have aids. In two previous studies on aids for guided navigation (Burnett & Lee, 2005; Parush et al., 2007), the authors did not specify if tests of spatial knowledge were anticipated or unexpected. Thus, the protection of internal validity in Experiments 2 and 3 may have come with a cost to external validity.

In future research, the role of attention could be directly assessed and measures of it could be used to predict individual differences in spatial knowledge. Also, it could be investigated in the context of the instructions. Relevant measures of attention include how it is selectively allocated to the environment, which may be assessed using eye-tracking and other measures, and measuring working memory capacity.

3.4 Measurement of Spatial Knowledge

As mentioned earlier, there are tradeoffs between the spatial updating measure used in Experiment 1 and the route replication task in Experiments 2 and 3. This work does not examine construct validity in measures of spatial knowledge, which are largely uninvestigated (Kitchin & Blades, 2002). Nevertheless, there are known differences between measures. Spatial updating reflects both route and survey knowledge, whereas reproducing routes is essentially a direct measure of route knowledge and novel route execution taps survey knowledge.

Since spatial updating was assessed by pointing at targets that were not visible, it required the offline retrieval of spatial representations (Waller & Hodgson, 2006). I contend this makes it a more general measure of environmental knowledge than reproducing routes. In Experiment 1, spatial updating entails route knowledge (travel between locations experienced during learning) and survey knowledge (novel relationships between locations, never directly experienced at learning). For example, if a participant traveled from A to B to C, standing at A and pointing to B is route knowledge, but standing at A and pointing to C is survey knowledge.

In the current work, spatial updating was likely a more challenging measure than reproducing routes for other reasons as well. There are numerous associative cues (e.g. signs, buildings, and environmental structure) at each intersection (decision point), which probably helped in recalling the route sequence. Also, for incorrect turns, the presence of unfamiliar cues might have helped corrected errors, increasing route accuracy.

A disadvantage of spatial updating is that its general nature may limit how meaningful it is as an indicator of environmental knowledge. If just successfully learning routes between locations is what matters, than route replication is a more direct measure because spatial updating can include survey knowledge. This is why route replication was used in Experiments 2 and 3. Generally, route knowledge is the relevant measure of navigation performance. Of course, relevance depends on the task (e.g. creating a map, finding a detour by executing a *novel* route when a known route is blocked). Since creating a map of environmental locations is often useful and is a transfer task measure, it was included in all studies.

Interpretation of Results in Experiments 2 and 3

In Experiments 2 and 3, the differing results for each type of navigation aid demonstrates that only a specific aspect of spatial knowledge was improved, not all aspects as hypothesized. For Experiment 2, the visual aids increased accuracy for route replication and for Experiment 3 cardinal directions, stereo and monaural, helped with executing a novel route. There are several reasons for these results.

The visual aids were primarily viewer-centered, providing spatial relations for the origins and destinations of route locations relative to current location and orientation. In contrast, Oliver and Burnett (2008) had unique landmarks at every intersection, which were included in the auditory guidance. Measures of survey knowledge were hypothesized to improve because both visual aids also depicted absolute spatial relations (targets relative to other targets). However, these relationships were updated egocentrically with translations and rotations; this is a probable explanation for why only route knowledge increased. Previous work using beacons assessed landmark and route knowledge (Waller & Lippa, 2007), but did not measure non-directional configural knowledge (i.e. map construction). Therefore, given that both the dynamic signpost and the beacons were present, it is unlikely that only beacons, despite specifying multiple, distant locations simultaneously, can promote non-directional survey knowledge.

Conversely, cardinal directions, effectively augmented directional survey knowledge assessed by executing a novel route. Unlike Experiment 3, in most earlier research, spatialized audio was used for navigation without vision (Giudice & Tietz, 2008; Klatzky et al., 2006). The dominant source of information for Experiment 3 was visual, not auditory. Thus, with sighted navigation, the benefits of spatialized sound may be smaller compared to navigation without vision. In addition, combining egocentric directions with cardinal directions has been posited to improve encoding (Gugerty & Brooks, 2001). Cardinal directions were never presented as the only source of guidance in Experiment 3, rather they were always added on to the egocentric directions.

Combining the visual and auditory aids, although not tested, is likely to improve most aspects of spatial knowledge. Furthermore, this combined augmentation may have multiplicative benefits, rather than an additive ones, because memory recall improves with multimodal encoding (Tan, Stefanucci, Proffitt, & Pausch, 2001; Tulving & Craik, 2000) and combined aids could reinforce egocentric and exocentric spatial relations.

Ceiling Effects in Experiments 2 and 3?

Accuracy was high for all measures of spatial knowledge in Experiments 2 and 3. It is possible that ceiling effects obscured, to a degree, the effectiveness of the aids for augmenting guided navigation. The route reproduction task could be made more difficult by reversing the travel order at test, i.e. learn A to B and reproduce the route from B to A. Also, introducing a time delay between learning and testing would decrease accuracy. Despite the high accuracy, augmentation still improved spatial knowledge in Experiments 2 and 3, albeit only for particular measures of spatial knowledge. Nevertheless, ceiling effects could have reduced power for detecting effects, particularly small ones. However, small effects are not meaningful for augmenting navigation, nor were the sample sizes big enough to detect small effects (i.e. 80% power for $d = .20$ needs $N = 620$ for one-tailed comparisons, $N = 788$ for two-tailed comparisons).

3.5 Applicability of Aids and Future Possibilities

Besides the specificity of how spatial knowledge is improved, both types of aids have limitations in their applications. The visual aids have technical limitations for use in a GPS system, whereas the use of cardinal directions may be restricted by environmental structure. A grid layout or straight roads would be ideal, but headings like "northwest" may still be effective and changes in heading from a road that curves could be updated accordingly.

Implementation of the visual aids would require augmented reality (Azuma, 1997), overlaying virtual content on the real-world. Typically this is done on a display screen with real-world shown through the feed from a video camera. The signpost and virtual beacons could be used to denote the spatial locations of the origin and multiple destinations, overlaid on real-world images from a video camera displayed on the screen of a GPS or smart phone. However, Experiment 2 did not look at aids on a small display screen. Therefore, a more promising, but speculative alternative is adding the visual aids to the heads-up display (HUD) of the windshield of an airplane. The HUD provides information like altitude, speed, and pitch. Since the visual aids boost route knowledge, a strong potential application is augmenting route knowledge of runways, which could be potentially useful for navigation during landings. However, the experiment did not directly assess that particular use for the visual aids.

The spatialized cardinal directions would be relatively straightforward to implement on a GPS system because they only require stereo sound. However, the environment has to have a grid structure or straight roads, so its application is constrained. In addition, novel route execution improved equivalently even when the cardinal directions were monaural.

The augmentation with spatializing cardinal directions could also be extended by adding salient environmental features (e.g. river or highway) or global landmarks (e.g. a mountain) to the auditory guidance. For example, “Turn right, heading north towards the mountain.” This augmentation is dependent on the availability of salient environmental features and requires customization for different environments. These restrictions of availability and customization are similar to the ones with Oliver and Burnett (2008) method of augmenting auditory guidance by including landmark descriptions in the turn directions. Finally, combining the visual aids and the auditory aid would potentially improve accuracy for reproducing routes and constructing a map.

3.6 Conclusions

In this work, I reviewed research pertaining to the components of active navigation and aids for improving spatial knowledge. In Experiment 1, I found less accurate spatial knowledge with guided navigation because spatial decision-making is absent. These results provide experimental evidence that the use of GPS guided navigation leads to impaired environmental knowledge. This suggests there could be serious consequences of a GPS system failing, especially when relied upon in an isolated location or in life or death situations, such as for law enforcement or the military. Furthermore, this finding also suggests that theories in navigation, which have typically emphasized the environment, are overlooking a critical element. Information processing for acquiring spatial knowledge is a function of the mode of learning. More specifically, the role of spatial decision-making in navigation and its processes are understudied (Garling & Golledge, 2000).

Effective navigation aids convey spatial relations by connecting features in the environment to the viewer (egocentric), environmental features to each other (exocentric), or both. Aids can improve environmental learning by emphasizing spatial relations using reference frames. The results from the experiments augmenting guided navigation indicates that the type of reference frames an aid uses may matter. Depending on whether the aid conveyed primarily egocentric relations or only exocentric relations, differential aspects of spatial knowledge were improved. Routes can be learned by memorizing the sequence of turns and/or using landmarks, neither requires using an environmental (exocentric) frame of reference. The predominantly egocentric visual aids increased accuracy for route knowledge. However, finding a novel route (i.e. traversing a path that was never learned between two locations) requires the use of exocentric spatial relations, provided by cardinal directions, and egocentric spatial relations. Creating a map requires survey knowledge, except that it is non-directional, because it entails the relative positions of the locations of targets to each other. Therefore, an accurate map can be created with just exocentric spatial relations, which may explain why cardinal directions improved finding a novel route. Overall, if possible, aids should be selected to have reference frames which correspond to navigational learning goals, so the appropriate level(s) of spatial knowledge are augmented.

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Appendix A

The table below contains descriptive statistics for the questionnaires (SBSOD scale, composite videogame experience measure, and the two videogame experience questions). Note the maximum score on the SBSOD scale is 105. Higher scores indicate greater levels of self-reported navigation ability. The composite videogame experience measure is a z-score; higher values indicate greater experience and more time spent playing action games.

The two videogame experience questions were:

1) Experience with first person video games (e.g. Halo, Unreal Tournament)

1	2	3	4	5	6	7
No experience						Tons of experience

2) Average number of hours per week spent playing first person video games? ___ hours

Descriptive Statistics of Questionnaires

Measure	SBSOD scale (scores range from 0 to 105)	Composite videogame experience (z-score)	Videogame experience (hours per week)	Videogame experience (overall experience)
		Experiment 1		
Males n = 31	M = 63.45 SD = 13.39	M = 1.09 SD = 1.78	M = 1.71 SD = 2.44	M = 4.97 SD = 1.66
Females n = 29	M = 56.89 SD = 15.96	M = -1.16 SD = .70	M = .07 SD = .24	M = 2.04 SD = 1.27
		Experiment 2		
Males n = 21	M = 73.91 SD = 12.46	M = .52 SD = .95	M = 1.55 SD = 2.17	M = 4.81 SD = 1.72
Females n = 19	M = 54.47 SD = 15.86	M = - .57 SD = .38	M = .05 SD = .23	M = 2.11 SD = 1.33
		Experiment 3		
Males n = 32	M = 61.50 SD = 5.82	M = .47 SD = .88	M = 1.21 SD = 2.13	M = 4.97 SD = 1.60
Females n = 28	M = 62.86 SD = 3.68	M = -.58 SD = .29	M = 0.00 SD = 0.00	M = 1.86 SD = 1.24

Note. One participant did not complete the video game experience questionnaire.

Appendix B

Table B1

Experiment 1: Correlations for Measures of Spatial Knowledge and Questionnaires

Measure	Pointing error	Map construction	SBSOD scale	Composite videogame experience
Pointing error	---	-.68**	-.32*	-.44*
Map construction		---	.19	.34**
SBSOD scale			---	.19
Composite videogame experience				---

Note. *$p < .05$, **$p < .01$.

Table B2

Experiment 2: Correlations for Measures of Spatial Knowledge and Questionnaires

Measure	Route replication	Novel route execution	Map construction	SBSOD scale	Composite videogame experience
Route replication	---	.30	.42**	.07	.05
Novel route execution		---	.21	.22	.13
Map construction			---	.20	.18
SBSOD scale				---	.44**
Composite videogame experience					---

Note. *$p < .05$, **$p < .01$. One participant's novel route score was excluded from the correlation table because it was more than three standard deviations below the mean.

Table B3

Experiment 3: Correlations for Measures of Spatial Knowledge and Questionnaires

Measure	Route replication	Novel route execution	Map construction	SBSOD scale	Composite videogame experience
Route replication	---	.16	.33*	.07	.17
Novel route execution		---	.30*	-.10	.26*
Map construction			---	.06	.25
SBSOD scale				---	-.07
Composite videogame experience					---

Note. *p < .05. One participant did not complete the video game experience questionnaire.

Appendix C

Examples of Route Accuracy

	Copter to gazebo	Gazebo to school	School to humvee	Humvee to tank	Tank to copter (novel route)*
Optimal length (segments)	5	5	5	6	8
			Accuracy Scores		
Perfect (matches route learned)*	100.00%	100.00%	100.00%	100.00%	100.00%
1 additional segment or optimal length, but different path than learning	87.50%	87.50%	87.50%	88.89%	90.91%
2 additional segments	75.00%	75.00%	75.00%	77.78%	81.82%
3 additional segments	62.50%	62.50%	62.50%	66.67%	72.73%
Maximum route length (1 segment from target)	50.00%	50.00%	50.00%	55.56%	63.64%
Maximum route length (2 segments from target)	37.50%	37.50%	37.50%	44.44%	54.55%
Maximum route length (3 segments from target)	25.00%	25.00%	25.00%	33.33%	45.55%
Maximum route length (4 segments from target)	12.50%	12.50%	12.50%	22.22%	36.36%
Maximum route length (5 segments from target)	0%	0%	0%	11.11%	27.27%

Note. *Excludes the novel route, which was never directly learned. Maximum route length is the number of optimal segments plus three additional segments. Not all possible scores for the novel route are included. The other route learning sequence was in the opposite direction (i.e. tank to humvee, humvee to school, etc).