Places and Regions in Perception, Route Planning, and Spatial Memory

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Zusammenfassung

Die Fähigkeit sich im Raum zu orientieren ist für die meisten Tiere von entscheidender Bedeutung. Die Orientierungsleistungen reichen von einfachem, stereotypen Verhalten bis hin zu komplexen, kognitiven Verhaltensleistungen. Eine Möglichkeit, die Vielzahl dieser Orientierungsleistungen zu klassifizieren, bietet das dem Verhalten zugrunde liegende Gedächtnis. Während z.B. Taxen, Orientierungsbewegungen als Antwort auf einen Sinnesreiz, ohne räumliches Gedächtnis möglich sind, sind Verhaltensleistungen wie die Planung und Navigation von Routen nur mit einer Repräsentation des Raumes, einem Ortsgedächtnis, möglich.

Sowohl in der Biologie als auch in den Kognitionswissenschaften ist das Ortsgedächtnis seit Jahrzehnten Gegenstand zahlloser Untersuchungen. Hauptaugenmerk wurde dabei meist auf die neuronalen Grundlagen und auf Eigenschaften des Ortsgedächtnisses, wie den Inhalt, das Format und die Organisation des im Ortsgedächtnis gespeicherten Wissens, gelegt. Die Pragmatik des Ortsgedächtnisses, dass heißt die Frage, wie räumliches Wissen für tatsächliche Navigtionsaufgaben genutzt wird, ist dagegen nur wenig untersucht. Die Planung von Routen zu Zielen, die sich außerhalb des sensorischen Horizontes befinden, ist eine der zentralen Aufgaben des Ortsgedächtnisses. Trotzdem ist sehr wenig darüber bekannt, wie wir Routen planen. Welche Mechanismen und Strategien erlauben es uns, scheinbar mühelos neue Routen durch bekanntes Terrain zu finden? Welche Gedächtnisinhalte nutzen wir während der Planung von Routen? Welche Eigenschaften des Ortsgedächtnisses beeinflussen unsere Auswahl von Wegen?

Diese Fragen waren Ausgangspunkt für die vorliegende Arbeit. Besonderes Interesse wurde dabei auf die Frage gelegt, welchen Einfluss die hierarchische Organisation des räumlichen Wissens auf die Planung von Routen hat. Die hierarchischen Theorien des Ortsgedächtnisses besagen, dass räumliches Wissen auf verschiedenen Detailebenen unterschiedlich stark abstrahiert wird. So werden z.B. benachbarte Plätze zu Regionen zusammengefasst. Diese Regionen und die räumlichen Beziehungen zwischen unterschiedlichen Regionen werden im Ortsgedächtnis auf einer höheren Abstraktionsebene repräsentiert. Hier werden fünf Navigationsexperimente vorgestellt, die den Einfluss dieser hierarchischen Struktur des Ortsgedächtnisses auf die Planung und Navigation von Routen untersuchen. Versuchspersonen erlernten verschiedene virtuelle Umgebungen, die in mehrere Regionen unterteilt waren, durch aktive Navigation. Anschließend wurden sie aufgefordert, möglichst optimale, d.h. kurze Wege zu finden, auf denen sie entweder einen oder mehrere Zielplätze ansteuern sollten.

Die Ergebnisse zeigen einen deutlichen Einfluss der Regionen in den Umgebungen auf das Routenplanungs- und Navigationsverhalten auf. Versuchspersonen minimieren den Anzahl der Regionen, die sie während einer Navigationsaufgabe überschreiten; sie bevorzugen, unabhängig von der genauen Position des Zieles, Routen, auf denen sie die Zielregionen schnellstmöglich betreten können; und, wenn Versuchspersonen zwischen mehreren Zielen wählen, dann steuern sie zuerst das Ziel an, das in der nächstgelegenen Region liegt. Diese Ergebnisse sind konform mit den hierarchischen Theorien des räumlichen Wissens, da sie bestätigen, dass Regionen explizit im Ortsgedächtnis repräsentiert sind. Die Ergebnisse zeigen außerdem, dass die hierarchische Organisation des Ortsgedächtnisses eine funktionale Bedeutung bei der Planung von Routen hat.

Aufbauend auf den empirischen Befunden wird die *fine-to-coarse* Planungsheuristik, ein kognitives Model entwickelt, das den Einfluss der Regionen auf die Planung von Routen beschreiben kann. Das Model zeigt, wie sowohl der Rechen- als auch der Gedächtnisaufwand während der Routenplanung durch den Einsatz von groben, abstrahierten räumlichem Wissen reduziert werden kann.

Abstract

The ability to orient in space is crucial for most animals. Orienting behaviors range from simple, stereotyped, behaviors to complex behaviors involving the use of cognitive functions. These different behaviors can be classified based on the extent to which they use different types of memory. For example, moving towards or away from a stimulus, can be performed without memory. Other orientation behavior, such as route planning, requires a spatial memory.

For decades, spatial memory has been studied in biology, psychology and in the cognitive sciences. The main focus concerned the neural basis of spatial memory and properties, such as the content, format and organization of the information stored in spatial memory. On the other hand, the pragmatics of spatial memory (the question of how spatial memory is used for navigation purposes) has been predominantly neglected. This is surprising, because planning a route towards a location that is beyond the sensory horizon is an everyday task that involves spatial memory. Yet, little is known about how such routes are planned. For example, which mechanisms and strategies allow humans to find novel routes through known territory? What information stored in spatial memory do we use during route planning? Which properties of spatial memory influence our selection of paths?

These questions were the starting point of this work. Special interest concerned the role of hierarchical organization in spatial memory for route planning and navigation behavior. Hierarchical theories of spatial representations propose that spatial memory contains nested levels of detail. For example, neighboring places are grouped together to form regions. These regions, as well as spatial relations between regions, are then represented at a super-ordinate level within the hierarchical representation of space. In this work five navigation experiments are reported that studied the influence of this hierarchical organization of spatial memory on human route planning and navigation. Subjects became familiar with different regions of virtual environments by active navigation. Subsequently, subjects were asked to navigate the shortest possible route connecting a start location with one or multiple target locations.

The results revealed a clear influence of the environmental regions on route planning and navigation behavior. Subjects minimized the number of region boundaries they had to cross along a route; subjects preferred routes that allowed them to enter a region containing a target sooner rather than later; and, in routes with multiple target regions, they chose to visit the closest target region first. These results are in line with the hierarchical theories of spatial representations, since they confirm that regions are explicitly represented in spatial memory. Moreover, the results demonstrate that the hierarchical organization of spatial memory has a functional role in human route planning and navigation.

Based on the empirical findings the *fine-to-coarse* planning heuristic, a cognitive model of region-based route planning, is developed. The model demonstrates how coarse, abstracted spatial knowledge can be used during route planning to reduce both computational effort and memory load.

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Overview

In the introduction (**chapter 1**) literature on navigation experiments, as well as on the form, structure and content of spatial memory is summarized. Particular interest is laid on the structure, that is, on the hierarchical organization of spatial representations. Up to now it is an open question whether this hierarchical organization influences human route planning and navigation.

In **chapter 2** the experimental setup and the general methods are described.

In **chapter 3** two navigation experiments in virtual environments are reported. In both of the experiments subjects first learned a virtual environment that was divided into different regions, and were then asked to complete navigation tasks. Here an influence of environmental regions on human route planning and navigation behavior was revealed.

In **chapter 4** the *fine-to-coarse* planning heuristic, a cognitive model of region-based route planning is developed. By using fine space information (place connectivity) for close locations and coarse space information (region connectivity) for distant locations simultaneously, the *fine-to-coarse* planning heuristic could account for the empirical data described in chapter 3.

In **chapter 5** the interaction of multiple navigation strategies is studied in two experiments. Here again the influence of the *fine-to-coarse* planning heuristic on route planning is demonstrated. Additionally, it was found that the distribution of target locations within the environments and the complexity of alternative paths influenced subjects' navigation behavior.

In **chapter 6** a navigation experiment is reported that studied the formation of regional information in human spatial memory during the learning of an environment. It is argued that regional information arises early during the process of learning an environment, because this coarse regional knowledge allows to employ navigation strategies in order to overcome missing or imprecise fine spatial information.

Chapter 7 summarizes the work and discusses the results in a broader context.

Chapter 1

Introduction

Consider planning a route in order to visit multiple locations in your home town. Assuming that no street-map is available, all information needed to plan the trip has to come from spatial memory. According to the number of targets, planning a reasonably short path can be a very complex and computationally expensive task. This is best demonstrated by the well known traveling salesman problem. The traveling salesman problem can be stated as follows: Given a number of cities and the cost of traveling from one to the other (usually distance), what is the cheapest round trip route that visits each city and returns to the starting city. The number of possible round trips is computed as N!, with N being the number of cities to visit. For visiting 5 cities and returning to the starting city 120 different round trips are possible, for visiting 8 cities, already 40320 different round tips are possible.

However, route planning is an everyday spatial task that humans solve surprisingly well. Obviously, rather than computing and comparing all possible paths for a given navigation task, humans use strategies and heuristics in order to reduce mental effort.

This work studies these strategies, heuristics and the memory structures underlying human route planning behavior by the means of navigation experiments.

This chapter is structured as follows: First, route planning is put in context with the rich repertoire of human navigational abilities. Second, properties of the spatial memory structures that comprise the information necessary to plan routes are discussed. Thirdly a number of navigation experiments in real and virtual environments that studied different aspects of spatial cognition are reviewed. Then the specific research questions and working hypothesis for this thesis are worked out.

1.1 Navigation

Navigation as defined by the Encyclopedia Britannica is the "science of directing a craft by determining its position, course, and distance traveled. Navigation is concerned with finding the way, avoiding collision, conserving fuel, and meeting schedules. Navigation is derived from the Latin navis, *'ship'*, and agere, *'to drive.'* It originally denoted the art of ship driving, including steering and setting the sails ...".

In the context of spatial cognition, Montello (2001) defines navigation as the 'coordinated and goal-directed travel through space' consisting of two components, namely locomotion and wayfinding[1]. Locomotion refers to the process of physically moving through space in response to sensory-motor information of the local surrounding. Typical locomotion tasks include course stabilization, obstacle avoidance and visual aiming, i.e. approaching a visible landmark. Locomotion does not require a long-term representation of space. Wayfinding on the other hand refers to the cognitive processes necessary to reach destinations. Tasks such as route planning, choosing between alternative routes, deciding on the sequence of destinations to visit, orienting towards non visible locations are referred to as wayfinding tasks. Wayfinding tasks involve a long-term representation of space.

In addition to the above classification, spatial abilities and spatial behavior can also be divided according to their complexity and according to the kind of memory needed to perform the behavior (e.g. Mallot, 1999).

Without memory. A surprisingly rich repertoire of spatial behavior can be performed without spatial memory, such as e.g. course stabilization within a corridor, obstacle avoidance or visual approach. This class of spatial abilities is very

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[1] The term wayfinding has originally been introduced by Lynch (1960) who defined wayfinding as based on "a consistent use and organization of definite sensory cues from the external environment.".

similar if not identical to what has just been described as locomotion. Braitenberg (1984) has demonstrated that a very simple machinery with two light sensors in front and two drives (effectors) in the rear can perform various spatial task. According to the (hard) wiring of sensors and effectors (inhibitory, excitatory, left-sensor with right-drive or left-sensor with left-drive and vice versa) the machinery performs obstacle avoidance, corridor following, attacking etc.

Working memory. Integration of information from multiple sensor sources over time allows to form a working memory. An example for a spatial behavior that can be explained by the integration of spatio-temporal information in working memory is path integration. The desert ant (*Cataglyphis fortis*) is well known for its path integration abilities. By continuously integrating its ego motion, the desert ant updates a so-called home-vector, i.e. a representation of the nest's position, that allows the ant to directly head homewards after long winding excursions (Wehner & Flatt, 1972; Müller & Wehner, 1988; Wehner, Michel, & Antonsen, 1994; Collett, Collett, & Wehner, 1999; Wehner, Gallizzi, Frei, & Vesely, 2002).
Path integration has also been found in other insect species (Collett & Collett, 2000), in birds (Collett & Collett, 1982; Regolin, Vallortigara, & Zanforlin, 1994) and in mammals (Mittelstaedt & Mittelstaedt, 1980; Gallistel, 1990; Alyan & McNaughton, 1999; Loomis, Klatzky, Golledge, & Philbeck, 1999).

Long-term memory. Spatial information stored in long-term memory allows for various spatial abilities ranging from stereotyped behavior to cognitive, i.e. goal dependent and flexible, behavior. An example for a stereotyped use of long-term memory of space is guidance, in which a target location is remembered by means of its spatial relations to landmarks. When approaching this target location movement decision are made in order to achieve or maintain the remembered relations to the landmarks. Cartwright & Collett (1982), e.g., have shown that honey bees remember a feeding location via a so-called snapshot of the visual scenery at this location. When returning to the feeding location, the bees compare their current view with the stored snapshot and calculate movement directions that increase the similarity between current view and remembered snapshot.

Another example for spatial behavior that can be achieved by remembered stimulus-response pairs is route learning and route following. If each decision place along a route is remembered, again, e.g., by storing a snapshot of the visual scenery, and the action required to move to the next decision point is remembered together with that snapshot, a route can be described as a series of 'recognition-triggered-responses' (Trullier, Wiener, Berthoz, & Meyer, 1997).

If an agent's behavior at a given decision point will vary according to its goals, i.e. the internal state, and does not solely depend on the sensory input and the experience of the agent, this behavior can be referred to as cognitive behavior. This goal-dependent flexibility is achieved by the acquisition of declarative memory of space, often referred to as a *cognitive map*. A central, everyday spatial behavior that is only accomplishable with a *cognitive map*-like representation of space is route planning (O'Keefe & Nadel, 1978).

In this work, route planning is defined as the process of selecting a path from a given starting location to a single or to multiple target locations, that are beyond the sensory horizon of the agent. The spatial information needed to plan the route therefore has to be retrieved from spatial memory.

1.2 Representations of Space

Mental representations of space are often referred to as *cognitive maps*. The term *cognitive map* has been introduced by Tolman (1948), who studied learning behavior in rats. After training rats to navigate a route through a maze in order to obtain food, Tolman could show that the rats were able to take novel shortcuts to directly approach the food source. This work has been very influential, because it demonstrated the existence of internal representations that reflect properties of the external world. In the first half of the 20th century behaviorism, the leading approach to understand behavior, explained behavior exclusively by the means of learned stimulus-response associations. However, such stimulus-response associations would not allow for novel short-cutting behavior, the rats must have learned the position of the food source with respect to the experimental room in order to approach it directly.

Since Tolman (1948), numerous other definitions of *cognitive maps* have been proposed, of which a small collection is listed below:

- O'Keefe & Nadel (1978) define a cognitive map as "*a representation of a set of connected places which are systematically related to each other by a group of spatial transformation rules*".

- Thinus-Blanc (1988) defines a cognitive map as an *"allocentrically organized representation of environmental features"*.

- Gallistel (1990) defines a cognitive map as *"a record in the central nervous system ... used to plan movements through the environment"*.

- Montello (2001) defines a cognitive map as including *"knowledge of landmarks, route connections, and distance and direction relations; non spatial attributes and emotional associations are stored as well."*

- Gärling, Böök, Lindberg, & Arce (1991) define *cognitive maps* as *"long-term stored information about the relative locations of objects and phenomena in the everyday physical environment"*.

As can be seen from these definitions, there is little more than a broad consensus. To the author's view a *cognitive map* is a declarative memory of space that allows for goal-dependent, flexible spatial behavior such as route planning and navigation to non-visible targets.
Anyway, the term *cognitive map* is somewhat misleading, because it triggers the map in the head metaphor, suggesting that spatial memory is a flat, 2-dimensional, street-map like representations of space. First criticism of the map metaphor is already found in *The image of the city* (Lynch, 1960, p. 87), where Lynch states that a representation of space is *"not a precise miniaturized model of reality, reduced in scale and consistently abstracted"*. In the following empirical evidence is reviewed that contradict flat, two-dimensional representations of space.

Representations of space or *cognitive maps* can be distinguished along the dimensions format, structure and content, all of which are discussed later in that chapter. For this work it is especially important to point out the distinction between the dimensions format and structure, because both have been used to distinguish between hierarchical and non-hierarchical organization of spatial memory. The format describes the kind of information underlying a spatial representation. The structure on the other hand describes whether a spatial representation is hierarchical or non-hierarchical. Hierarchical representations entail multiple levels of detail, that is, the same information is represented at different levels of abstraction.

1.2.1 The format of spatial representations

Representations of large scale spaces do have very special demands. Information about the environment that has been acquired at different locations, at different times and with different senses have to be integrated with information about the spatial relations between these locations into a single representation. Spatial memory can therefore be seen as an integration stage at which all spatial information has to be compatible. The format of such a representation describes the kind of data underlying this spatial memory.

Byrne (1979) suggested that memory for urban environments is realized in topological networks of places. In such graph-like representations nodes correspond to locations, while the edges represent the paths between nodes. In this work the concept of graph-like representations of space in which places, views, local maps or other representations of locations are interconnected without the need to conserve the exact metrical relations of the real world, is emphasized and contrasted with map-like 2-dimensional representations of space, as put forward by the literal meaning of the phrase *cognitive map* and as modeled in robotics as occupancy grids.

Evidence for graph-like representations of space has come from navigation experiments in animals and humans. For example, the desert ant *Cataglyphis fortis* is well known for its path integration abilities, which are achieved by continuous updating of a so-called home-vector. However, on familiar routes, desert ants also steer by visual landmarks and navigate paths that consist of several segments with different directions (Collett, Dillman, Giger, & Wehner, 1992). Collett, Collett, Bisch, & Wehner (1998) have shown that these segments partly consist of stored visual landmarks, associated with local vectors, that are recalled at the appropriate place (see also Collett, Collett, & Wehner, 2001; Collett & Collett, 2002). Similar results also come from other insect species, as e.g. the honeybee (Menzel, Geiger, Joerges, Müller, & Chittka, 1998; Wehner, Michel, & Antonsen, 1996). Such a spatial memory, composed of landmarks and associated movement vectors, is best described as a graph in which landmarks correspond to nodes and the stored local vectors correspond to edges, reflecting the action to be performed in order to move between nodes.

Graph-like representations have also been used in artificial intelligence approaches and as cognitive models of human spatial memory (e.g. Kuipers, 1978, 2000; Leiser & Zilbershatz, 1989; Chown, Kaplan, & Kortenkamp, 1995). Schölkopf & Mallot (1995), e.g., have proposed and modeled a view graph representation of space. In a view-graph each node corresponds to a snapshot of the visual scenery at a given location. Nodes are interconnected by edges that constitute the behavior necessary to move between the corresponding nodes. The view-graph is a parsimonious representation of space that allows for complex navigation behavior such as route-planning.

In navigation experiments in virtual environments, Gillner & Mallot (1998) have shown that human subjects store local elements (i.e. places or views with associated movement instructions and expected outcomes) in spatial memory (see also Mallot & Gillner, 2000). These local elements did not have to be globally consistent, which contradicts map-like representations of space. Additional evidence for graph-like representations of space in humans was provided by Steck & Mallot (2000). Steck & Mallot have shown that subjects who learned a virtual environment containing both global and local landmark information, did not perceive and report a conflict, when global and local landmark information was set in conflict. Moreover, subjects who relied on global landmark information in the conflict situation, showed good way-finding performance if only local landmark information was provided, and vice versa. Again, the fact that subjects had access to both global and local landmark information while they did not perceive and report conflicts suggests that spatial information is not integrated in a single 2-dimensional map-like representation of space, but contains bits and pieces of information that are not necessarily tested for consistency (see also Tversky, 1993). The above evidence demonstrates that graph-like representations of space are both, ecologically sensible (i.e. minimalistic) and sufficient.

Additional evidence against map-like representations of space was reported by Sadalla, Burroughs, & Staplin (1980), who could show that spatial representations may violate metric axioms. The metric symmetry axiom states that a distance between point A and point B must be the same as the distance between point B and point A. Sadalla et al. (1980) examined whether distances from a ′reference′ point to a ′non-reference′ point were perceived as being symmetric. Reference points were defined as well known and historically important locations. Subjects had to judge distances either from a ′reference′ point to a ′non-reference′ point or vice versa. Distances from ′reference′ points to ′non-reference′ points were judged smaller than distances from ′non-reference′ points to ′reference′ points.

1.2.2 The structure of spatial memory (hierarchical theories of spatial representations)

Hierarchical theories of spatial representations propose that spatial memory contains nested levels of detail (e.g. Hirtle & Jonides, 1985; McNamara, 1986; Stevens & Coupe, 1978). According to subjective perception and physical properties of space, geographical entities are grouped together and form super ordinate entities in graph-like representations of space.
Non-hierarchical theories state that spatial memory does not contain hierarchies, i.e. all information available is stored at the same level of detail. The prototypical example for a non-hierarchical representation is probably an image, preserving the metric spatial relations among locations (e.g. Kosslyn, Ball, & J.Reiser, 1978; Thorndyke, 1981).
The critical difference between hierarchical and non-hierarchical theories of spatial memory concerns the type of information stored in the corresponding representations. In contrast to non-hierarchical representations, hierarchical representations may simultaneously contain information of different ontological status (e.g. single landmarks, sets of landmarks, regions, etc.).

Evidence for hierarchical theories comes from a wide variety of experimental paradigms that reveal systematic distortions in human spatial memory. Stevens & Coupe (1978), e.g., have shown that the relative directions of cities are distorted towards the directions of the states they reside in. Subjects usually judged Reno (Nevada) to be north-east of San Diego (California), although the correct direction is north-west. Stevens & Coupe suggested that subjects' knowledge about the super ordinate spatial relations (Nevada being east of California) influenced subjects' direction judgments. Similar distortions have been shown for other city pairs and for artificial maps containing cities and borders. Moreover, Wilton (1979) has shown that directional judgments are faster when judging directions between locations across regions than within regions. The effect of barriers and environmental regions on distance estimations provide further evidence for hierarchical theories. Generally speaking, distance estimations across barriers or region boundaries are exaggerated as compared to distances that do not cross barriers (Kosslyn, Pick, & Fariello, 1974; Cohen, Baldwin, & Sherman, 1978; Thorndyke, 1981; Newcombe & Liben, 1982).

Strong evidence for hierarchical organization of spatial representations is provided by Hirtle & Jonides (1985) and McNamara (1986). Hirtle & Jonides (1985) examined subjects' spatial memory structure of a natural environment, namely Ann Arbor campus in Michigan. Subjects had to recall 32 familiar landmarks of Ann Arbor campus repeatedly. By applying the ordered-tree algorithm developed by Reitmann & Rueter (1980) to the recall protocols, Hirtle & Jonides (1985) obtained the individual hierarchical clustering of the 32 landmarks in Ann Arbor campus for each subject. Subjects also judged relative and absolute distances between pairs of the 32 landmarks. While in relative distance estimations subjects underestimated the distances between landmarks in the same cluster, in absolute distance estimations distances between clusters were overestimated (similiar results have been obtained by Holding, 1992).

McNamara (1986) used a spatial priming paradigm to study the structure of human spatial memory (see also McNamara, Ratcliff, & McKoon, 1984; McNamara & LeSueur, 1989; McNamara, Hardy, & Hirtle, 1989). Subjects learned a spatial layout of objects that was divided into four regions, either by active navigation or by studying maps. In the subsequent recognition task, object names were presented on a computer screen one at a time. Subjects had to decide whether or not the named object was present in the layout they had learned. McNamara (1986) could show that subjects' reaction time was faster when the preceding object was in the same region of the layout, than when the preceding object was in a different region of the layout. In subsequent direction- and distance judgments subjects distorted directions to correspond with super-ordinate spatial relations and they underestimated within region distances while they overestimated between region distances.

1.2.3 The content of spatial representations

Landmarks are probably the most commonly accepted constituents of spatial memory. Cohen & Schluepfer (1980) defined landmarks as *"unique visual configurations which are used as course-maintaining aids. Landmarks, then, can be such things as buildings, trees, signs, or intersections - any spatially meaningful visual configuration."*. It shall be noted that landmarks do not necessarily have to be visually identifiable (see Jansen-Osmann, 1998; Loomis, Klatzky, & Golledge, 2001, for auditory landmarks) as accounted for by Sorrows & Hirtle (1999): *"A landmark may be any element in an environment that is external to the observer and that serves to define the location of other objects or locations."*.

Allen, Kirasic, Siegel, & Herman (1970) have shown that children prefer to choose eye-catching objects as landmarks, although those objects were not uniquely specifying a single location and were therefore unsuitable landmarks. Not only the physical properties, but also the position of a landmark within an environment determines if it is encoded in spatial memory. Aginsky, Harris, Rensink, & Beusmans (1997), e.g., monitored subjects' spatial knowledge of an virtual environment during the learning of a route. They found that only relevant spatial information, i.e. landmark information in the vicinity of choice points, was retained (see also Cohen & Schluepfer, 1980; Allen et al., 1970). Furthermore Aginsky et al. argued that one group of subjects based their wayfinding decisions on visually recognized decision points. While this group did not integrate the different decision point into a survey knowledge, a second group of subjects integrated spatial knowledge into a survey map.

Gärling, Böök, Lindberg, & Arce (1990) have shown that elevation is encoded in spatial memory. From memory subjects were able to reliably discriminate two locations in their home town with respect to elevation. Geographical slant has been shown to improve navigation and wayfinding performance as well as directional judgments in a virtual environment setup, providing additional evidence that slant or height information is integrated in spatial memory (Steck, Mochnatzki, & Mallot, 2003; Restat, Steck, Mochnatzki, & Mallot, 2003). Slant information could be used as a global compass.

The representation of distance in spatial memory has been investigated in numerous studies. Distance estimates of a route, e.g., are influenced by landmarks, signs, buildings, junctions, barriers and branches along the routes (see Cohen et al., 1978; Sadalla, Staplin, & Burroughs, 1979; Sadalla & Magel, 1980; Thorndyke, 1981; Newcombe & Liben, 1982; Allen & Kirasic, 1985; Allen, Kirasic, & Beard, 1989; Montello, 1997; Berendt & Jansen-Osmann, 1997). Generally, an increasing number of features along a route results in increased distance estimates. The *feature-accumulation hypothesis* states that the features along the route distort subjects' distance-estimations of a route via their number, salience or retrievability (e.g., Sadalla & Magel, 1980), while the *route-structuring hypothesis* states that routes are subdivided into stretches and that overestimated distance judgments between these stretches account for the effect (e.g., Allen & Kirasic, 1985). Berendt & Jansen-Osmann (1997) suggest that the *route-structuring-effect* is a special case of the *feature-accumulation effect*. In their study, houses (features) along a route had the same influence on distance estimations as junctions (structure). Rothkegel, Wender, & Schumacher (1998) investigated the representation of distances measuring reaction times. Reaction times increased with increasing number of objects along the route, but not with increasing path length, suggesting that only distances between objects are explicitly encoded while distances for whole paths were inferred.

Navigation experiments in different insect species suggest that movement vectors associated with landmarks are encoded in spatial memory (see section 1.2.1, for an overview see Collett & Collett, 2002). Cartwright & Collett (1983) showed that bees store local views (snapshots) in order to characterize a location. When returning to that location, bees have to match their current visual percept with the stored snapshot. By combining memorized snapshots with vectors, describing the behavior necessary to move between the locations corresponding to the memorized views, a view-graph representation of space is generated (see section 1.2.1 and Schölkopf & Mallot, 1995; Franz, Schölkopf, Mallot, & Bülthoff, 1998).

1.2.4 Representations for Actions (working memory)

In order to use spatial information stored in long-term memory for tasks such as route planning or spatial reasoning, the corresponding information has to be made available in working memory (also referred to as short term memory by some theorists). According to Baddeley (1986), working memory is a temporary, attention-demanding store with limited capacity that is used to process information obtained from sensory input or retrieved from long-term memory structures. In other words, working memory is that part of the memory system, that keeps information active while this information is used (see also Baddeley & Hitch, 1974; Baddeley, 1992, 2003).

Working memory is composed of (at least) three components: the *central executive*, a control system that coordinates information in the two storage systems, the *phonological loop* and the *visuo-spatial sketchpad* (also referred to as *visuo-spatial scratch pad*). The *visuo-spatial sketchpad* holds information in a spatial format (e.g., the spatial relation between a landmark and the ego-position and -orientation), the *phonological loop* on the other hand holds auditory information. The *central executive* mediates between the subsystems of working memory and long-term memory. Representations are maintained in the subsystems of working memory by periodic rehearsal.

The ability to hold information in working memory is limited, both by time and capacity. The capacity of working memory is assumed to be limited to around 7±2 items or chunks of information. Items will stay in working memory for a relatively short period of time (approximately 20 seconds) if item rehearsal in working memory is prevented. However, the length of time for which items remain in working memory can be modified by attention. The more attention is paid to the items in working memory, the more rehearsal will take place.

The need to subdivide the *visuo-spatial sketchpad* into a spatial memory component and a visual memory component was indicated by studies, that revealed strong interferences between two spatial working memory tasks, while less interference was found between a spatial working memory task and visual working memory task (see Logie & Baddeley, 1990; Della Sala., Gray, Baddeley, Allamano, & Wilson, 1999).

So far, little work has been attributed to the role of the visuo-spatial sketchpad in large scale spatial tasks involving navigation. Baddeley (2003) stated that the *visuo-spatial sketchpad* is likely to *"have a role in acquiring semantic knowledge ... for understanding complex systems ... (and) for spatial orientation and geographic knowledge. So far, there seems to have been little work on this potentially important topic."*

1.3 Neural Substrate of Spatial Memory

In the 1970s the first studies were reported that described cells within the rat hippocampus that modulated their firing rate according to the position of the animal in an experimental environment (O'Keefe & Dostrovsky, 1971; Ranck, 1973; O'Keefe, 1976; O'Keefe & Nadel, 1978). These so-called *place cells*, presumably pyramidal cells, fire in complex bursts as an animal moves through a specific region within an environment. This region is referred to as the cell's *place field*. Place cell activity and place fields are surprisingly stable: information from all sensory system are used to establish and maintain place cells and place fields, and, place fields remain stable if environmental features change. For example, place fields that have been established during training in the light, also remain in the dark (O'Keefe & Conway, 1978; Muller, Stead, & Pach, 1998). A sufficient number of hippocampal *place cells* with different place fields would allow to map an entire environment (O'Keefe & Nadel, 1978; Wilson & McNaughton, 1993) and could constitute the basis for behavior such as short-cutting and novel route planning. The hippocampus would therefore be just the right brain structure to look for the 'cognitive map'.

Supporting evidence for the role of the hippocampus for spatial learning and spatial memory has also come from lesion studies in different experimental paradigms, such as the radial-arm maze task and the water maze task. In the radial arm maze animals learn to alternate between the arms of a maze that radiate from a central platform in order to retrieve food pellets (e.g. Olton & Samuelson, 1978). In this task hippocampal lesions resulted in working memory impairment. If every arm was baited, control animals rarely visited a single arm twice, while animals with hippocampal lesions visited the same arm several times (Baddeley & Hitch, 1974). If, on the other hand, only four out of eight arms were baited, animals with hippocampal lesions had greater difficulties in learning which arms were baited as compared to control animals. Hippocampal lesions also impaired spatial learning in the Morris water maze task (e.g. Morris, Garrud, Rawlins, & O'Keefe, 1982), in which the rats had to find a submerged platform in order to escape the water (Morris, 1981). These results suggest that hippocampal lesions not only impair working memory, but also long-term memory consolidation.

Additional evidence for the crucial role of the hippocampus for spatial memory and navigation came from functional neuroimaging studies in humans. In an navigation experiment Maguire, Burgess, Donnett, Frackowiak, Frith, & O'Keefe (1998) have shown that activation of the right hippocampus was associated with knowing places and navigating between these places in a virtual environment. In another study in which subjects had to find a way out of an unknown maze, significant activation in the right hippocampus was reported (Grön, Wunderlich, Spitzer, Tomczak, & Riepe, 2000). In both of these studies it has been argued that the hippocampus provides an allocentric representation, i.e. an observer independent representation of spatial relation between objects, that is used to compute directions and distances between any known locations within an environment. Structural MRI's of the brains of navigational experts, London taxi drivers, have revealed an increase of hippocampal size as compared to a control group (Maguire, Gadian, Johnsrude, Good, Ashburner, Frackowiak, & Frith, 2000; Maguire, Spiers, Good, Hartley, Frackowiak, & Burgess, 2003), perhaps reflecting their detailed representation of the city.

However, the theory that the hippocampus serves primarily as a representation of space used for navigation and route planning, has been challenged. It is important to stress that hippocampectomy impaired but did not prevent spatial learning in the Morris water task, i.e. rats were slower but still able to learn the task (e.g. Morris et al., 1982). Moreover Alyan, Jander, & Best (2000) have shown that hippocampectomized rats can learn to recognize places using constellations of distinct landmarks.

Additionally a number of studies suggest that place cells not only code pure spatial information but simultaneously non-spatial information as, e.g., speed information, directionality and match vs no-match information.

McNaughton, Barnes, & O'Keefe (1983) have shown that the firing rate of hippocampal place cells correlate with the speed at which the animals move through the environment. In a modification of a T-maze Wood, Dudchenko, Robitsek, & Eichenbaum (2000) have trained rats to continuously alternate left turns and right turns from the central arm while recording from the hippocampus. Wood et al. have described cells that fired in the central arm of the T-maze only if rats were on left-turn trials but not on right-turn trials and vice versa. These cells do code spatial information, since they always fire in the same place, but at the same time these cells encode information specific to one kind of trial episode. In a water maze task Fyhn, Molden, Hollup, Moser, & Moser (2002) found that some neurons that coded for the position of a submerged platform stopped firing as the platform was removed and could not be found by the rats. Other neurons started firing at the corresponding location only if the platform was unexpectedly not found.

In a radial arm maze, Hölscher, Jacob, & Mallot (2003) have recorded hippocampal neurons that fired in a particular arm, only if that arm was baited, while the neurons were silent if food reward was expected but not found in a second run.

The addressed studies demonstrate that, while place cells do convey information about space, they also encode much more than just spatial information (for an extensive overview see Hölscher, 2003). Taken together, restricting the role of the hippocampus as the seat of spatial memory, is too simple.

1.4 Navigation Experiments

Most navigation experiments were designed to study properties of spatial memory. In section 1.2 numerous navigation experiments studying the format and the content of spatial representations have already been described. Here further navigation experiments studying different aspects of spatial cognition are introduced.

1.4.1 Navigation experiments investigating properties of the environment

O'Neill (1992) investigated the influence of floor plan complexity on human wayfinding performance. He could demonstrate that wayfinding performance decreased with increasing plan complexity. Also O'Neill found an interaction between plan complexity and familiarity on wayfinding, suggesting that the complexity of an environment has less of an impact on wayfinding performance as familiarity increases. O'Neill (1991) introduced the inter-connection density index (ICD) as an analytic measure of floor plan complexity. Basically the ICD of a decision point increases with increasing number of different paths or movement possibilities. One problem with the ICD measure of complexity is that the ICD index for the floor plan is calculated by averaging over all ICD indices of choice points within an environment. This is problematic, because by averaging, a floor plan that comprises a large number of decision points is not necessarily more complex than an floor plan that only comprises a single decision point. This contradicts the common sense concept that complexity is somehow correlated to the size of environments (Franz, 2003). Another complexity measure is described by Raubal & Egenhofer (1998) who also used the number of choices at a decision point as one measure for the complexity of a given wayfinding task, additionally cues such as signage at this decision points are taken into account.

Heye & Timpf (2003) introduced a measure to compare the physical complexity of alternative routes in public transportation networks. In order to derive the complexity of a route, the complexity of all transfer points along the route are summed up. The complexity of single transfer points mainly depends on the number of stops within the transfer point and the number of possible changes of transportation mode.

Architectural design and its influence on human wayfinding and the mental representation has been studied by Werner & Long (2003). They could demonstrate that the misalignment of reference systems impairs the users ability to integrate spatial information across multiple places. Werner & Long suggested that reference axes should be consistent throughout a building in order to support navigability.

Janzen, Herrmann, Katz, & Schweizer (2000) investigated the influence of oblique angled intersections within an environment on wayfinding performance. When navigating arrow-fork intersections, subjects' error rate depended on which branch they entered the intersection (see also Janzen, Schade, Katz, & Herrmann, 2001).

1.4.2 Navigation experiments investigating gender differences in spatial cognition

Differences between genders in navigation and wayfinding strategies have been subject of numerous studies. Generally, sex-differences in spatial cognition are supposed to be one of the most reliable of all cognitive gender differences in humans (Moffat, Hampson, & Hatzipentalis, 1998).

Astur, Ortiz, & Sutherland (1998), e.g., have developed a virtual version of the Morris water maze task for humans. Subjects were placed in a virtual pool that was surrounded by distal cues and were instructed to escape from the water as quickly as possible by navigating towards a hidden platform. During training Astur et al. recorded 'swimming' time until reaching the platform, in the test phase the platform was removed and the time subjects spent in the corresponding quadrant searching for the platform was recorded. Results revealed a strong gender effect: males swam for shorter time to find the platform, and after removing the platform males spent more time in the quadrant where the platform has previously been. While this study suggested a gender difference favoring males in spatial performance, other studies have reported the use of different aspects of the environment (e.g., global and local landmarks) and the use of different orientation and navigation strategies between subjects (e.g., Lawton, 1994, 1996; Sandstrom, Kaufman, & Huettel, 1998; Lawton & Kallai, 2002), rather than fundamental performance differences. Basically these studies state that male subjects rely more on global landmark configurations or global reference systems, while female subjects tend to rely on local landmark information and route information.

In a neuroimaging study Grön et al. (2000) have reported gender differences in brain activation as subjects searched their way out of a virtual three-dimensional maze. While there was as great overlap of brain area activation between genders, including the right hippocampus, Grön et al. report specific activation of the left hippocampus in males, and a specific activation of right parietal and right prefrontal cortex for females.

1.4.3 Navigation experiments studying mechanisms underlying route planning behavior

Although the form, structure and content of spatial memory have been extensively studied, little work has been attributed to the question which strategies, mechanism and heuristics underly human route planning behavior. In this section navigation experiments are reviewed that shed some light on the processes underlying route planning.

"Traditionally, the path selection problem has been ignored or assumed to be the result of minimizing procedures such as selecting the shortest path, the quickest path or the least costly path."[2] . Golledge (1995) studied which criteria are used in route selection when choosing between alternative routes from maps and when navigating routes in real environments. Golledge rated the criteria used during route selection and found (among other criteria) that subjects took into account the length of routes, the time to travel a route, the number of turns along a route and the aesthetics of the routes. Most importantly, Golledge argued that single selection criteria, such as minimizing distance, could not account for the variety of routes that subjects selected in his experiments, but that different criteria were applied in different environments.

Gärling & Gärling (1988) investigated pedestrian shopping behavior with respect to distance minimization in multi-stop shopping routes. Most shoppers, that minimized the distance of their shopping routes, first chose the location farthest away,

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[2] In R. Golledge (1995). Path selection and Route Preference in Human Navigation: A Progress Report. In A. Frank & W. Kuhn (Eds.), *Spatial Information Theory: A Theoretical Basis for GIS (COSIT'95)*. Number 988 in *Lecture Notes in Computer Science*

most probably to minimize effort to carry bought goods, and then minimized distances locally between shopping locations (see also Gärling, Säisä, Böök, & Lindberg, 1986). This so called locally-minimizing-distance (LMD) heuristics, also often referred to as the nearest neighbor (NN) heuristic in artificial intelligence approaches (e.g. Golden, Bodin, Doyle, & Stewart, 1980), is known to generally lead to optimal or near optimal solutions in traveling salesman problems of small sizes.

Gallistel & Cramer (1996) studied vervet monkeys ability to navigate the shortest route connecting multiple locations, by arranging baited locations in a group of four to one side and a group of two to the other side (see figure 1.1a). Note that the nearest baited location of both food patches were equidistant from the starting point. An algorithm like the nearest neighbor algorithm (NN) predicts that the monkeys choose to first visit both of the food patches equally often. However, the vervet monkeys first visited the richer food patch in all trials. In this work this strategy is referred to as the *cluster-strategy*. Similar results have been obtained by Menzel (1973) investigating chimpanzees' performance in a modification of the traveling salesman problem. In a second experiment Gallistel & Cramer (1996) arranged baited locations in a diamond shape. If the monkeys intended to return to the starting position, because it was baited after the monkey left it, the monkeys generally chose the shortest route in this traveling salesman task (see solid route in figure 1.1b). Here a NN strategy would predict that the monkeys followed a different non-optimal route (see dashed route in figure 1.1b) for the first steps. Gallistel & Cramer (1996) concluded that the vervet monkeys' route planning algorithm not only took the first step into account (as predicted by the NN), but is indeed planning three steps ahead.

Christenfeld (1995) studied human subjects' preference to choose a certain route from a series of almost identical routes. In all conditions (route choice from artificial maps, from street maps or in real world environments) subjects had the choice between a number of routes that were identical with respect to metric length, target point and the number of turns. The only difference between the routes was when along the route subjects had to make a turn. In all conditions subjects delayed the turning decision as long as possible (see figure 1.1 c). Christenfeld speculated that this effect resulted from subjects' tendency to minimize mental effort, that is to say, subjects did not worry about where to turn until they had to turn. This strategy offers a possible explanation for the fact that people's route choices are often asymmetric; i.e. subjects choose different routes from A to

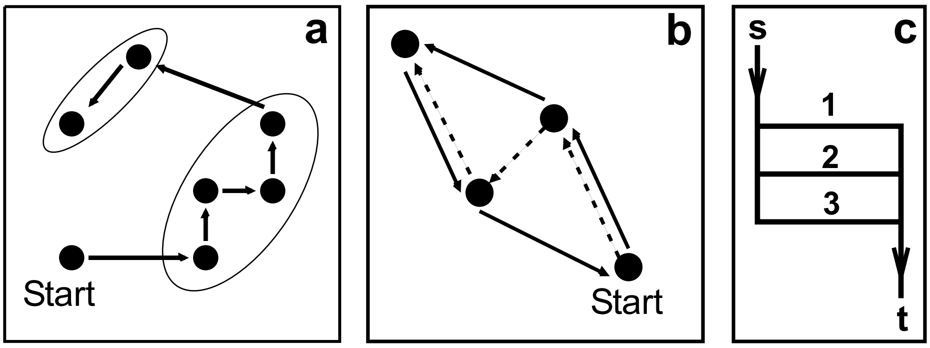

Figure 1.1: *a*: the unequal sides test by Gallistel & Cramer (1996) with a large and a small food patch; *b*: the dashed route was optimal, when the starting position was not re-baited, the solid route was optimal if the starting position was re-baited; *c*: when navigating from start (s) to target (t), subjects preferred route number 3 above the alternative routes with equal metric length, because route number 3 allowed to delay the turning decision as long as possible (Christenfeld, 1995).

B than from B to A (e.g. Stern & Leiser, 1988).

1.5 Research Questions and Working Hypothesis

Evidence for the hierarchical organization of spatial memory comes from a wide variety of experimental paradigms, including distance- and direction-judgments, recall procedures and reaction times (see section 1.2.2). However, although the ultimate purpose of spatial memory is to support navigation, very little is known about the influence of the hierarchical organization of spatial memory on the mechanisms, strategies and heuristics underlying human route planning.

One of the few studies on the role of regions for route planning (environmental regions are known to result in hierarchically organized spatial memory) investigated route planning from maps (Bailenson, Shum, & Uttal, 1998). Bailenson et al. formulated the *road climbing* principle, stating that instead of calculating the globally shortest route, subjects relied on routes that allowed to leave the region containing the start place sooner rather than later. In addition subjects take the straightness and length of the initial route segment into account (Bailenson, Shum, & Uttal, 2000). This so-called Initial Segment Strategy (ISS) states that subjects prefer routes with the longest initial straight segment above alternative routes of equal length.

However, the question whether or not the hierarchical organization of spatial memory influences human route planning and active navigation behavior in large scale environments is still an open question.

This work studies the impact of hierarchical memory organization on human route planning behavior by the means of navigation experiments. The work is motivated by the following working hypothesis and research questions:

- *Hypothesis 1*: The ultimate purpose of spatial memory is to support navigation. The properties of spatial representations should therefore be reflected in navigation behavior. If human spatial memory contains regional information (i.e., if spatial memory is hierarchically organized), these regions will influence human navigation behavior.
- *Hypothesis* 2: The hierarchical organization of spatial memory is used to reduce the computational effort of route planning tasks.
- *Hypothesis* 3: If regions within an environment are perceived during the learning of a new environment, these regions will be encoded in spatial memory sooner rather than later, because (i.) by structuring space, learning will be facilitated; and because (ii.) regional knowledge, i.e., coarse spatial information, allows to employ heuristics and strategies that could compensate for missing or imprecise fine spatial knowledge.

Consequently the three main research questions are as follows:

1. Do regions within an environment influence human route planning and navigation behavior?
2. By which mechanism is regional information used for route planning?
3. When does regional information appear in spatial memory during the learning of an environment?

These three main research questions entail a number of sub-questions:

- How does the use of hierarchies for route planning has to be modeled such that human navigation behavior is reflected?
- Is computational effort reduced by the use of regional information during route planning?
- How do region-based route planning strategies interact with other route planning strategies?

In the following, five navigation experiments are reported that were designed to investigate the research questions. Also a cognitive model of region-based route planning is developed that can account for the empirical data.

Chapter 2

General Methods

All experiments presented in this work were conducted using virtual reality technology. Subjects actively navigated through the virtual environments in the egocentric perspective and executed a series of navigation tasks.

Compared to real world experiments, the use of virtual reality technology for navigation experiments has two major advantages. Firstly, it allows for exact control of the visual stimuli presented, and secondly, one can carry out the experiments in environments created to exactly match the experimental demands.

2.1 The Experimental Setup

Experiments were conducted in the Virtual Environments Laboratory of the Max Planck Institute for Biological Cybernetics. For all experiments, a particular virtual environment was created using the software Multigen Creator (MultiGen-Paradigm). A detailed description of the virtual environments is given in the methods sections of each experiment (see sections 3.1.2.1, 3.2.2.1, 5.1.2.1, 5.2.2.1 and 6.2.1).

The visual scenery was rendered on a three-pipe Silicon Graphics Onyx2 InfiniteReality II (Silicon Graphics Inc., Mountain View, CA), running a C++ Performer simulation software. The scenery was then projected by means of three CRT projectors (Electrohome Marquee 8000; Electrohome Limited, Kitchener, Ontario, Canada) on a large half-cylindrical screen (7 m diameter and 3.15 m height)

Figure 2.1: The experimental setup. The pictures display the same experimental room. Subjects were either seated at a desk (experiment 1) or on a bicycle trainer (experiment 2-5).

with a rate of 36 frames per second and an overall resolution of approximately 3500x1000 pixels.

Subjects were seated in front of this screen (see figure 2.1) either at a table (experiment 1) or on a bicycle trainer (experiment 2-5). The experimental setup allowed for a 180° horizontal and a 50° vertical field of view. The simulation software guided subjects through the experiments, presented pictures of the navigation goals on the projection screen, and recorded the data. A detailed description of the setup can be found in van Veen, Distler, Braun, & Bülthoff (1998).

2.2 Procedure

The general procedure for the first four experiments was very similar and shall therefore be introduced here, the experimental procedure of experiment 5 is explained in detail in chapter 6. Experiment 1-4 were divided into three different phases: a free exploration-, a training- and a test-phase.

Exploration Phase. During the 10 minute exploration-phase subjects could explore the environment. Subjects were instructed to move around in the environment, pay attention to the landmarks and learn the layout of the environment and the positions of the landmarks.

Training Phase. The training phase was introduced to ensure that subjects had learned the environment before they entered the test phase. Subjects were therefore asked to complete six navigation tasks taking the shortest possible routes. For each training-route subjects were teleported to the starting place of the route. The target place was specified by presenting a picture of the landmark associated with the target place. The image was superimposed on the screen. If subjects failed to find the shortest possible route, an error was recorded and the navigation task was repeated until subjects solved the task taking the shortest possible route.

Test Phase. The navigation tasks of the test phase and the specific procedure of the test phase is explained in detail in the methods section the corresponding experiments (see section 3.1.2.2, 3.2.2.2, 5.1.2.2 and 5.2.2.2).

Chapter 3

Route Planning in Regionalized Environments

In this chapter two navigation experiments are presented that studied the influence of regions within an environment on human route planning behavior. It is argued that the regions are explicitly represented in spatial memory, as suggested by the hierarchical theories of spatial memory, and that route planning takes into account the hierarchical structure of spatial memory.

3.1 Experiment 1

3.1.1 Purpose

This study was designed to reveal the influence of environmental regions on route planning and navigation behavior. Subjects learned a virtual environment that was divided into different regions. After learning the environment, subjects were asked to execute a series of navigation tasks comparable to shopping routes, in which they had to find the shortest route connecting multiple target-places. The critical navigation tasks in the test phase provided multiple solutions that only differed with respect to the region-characteristics, as explained below.

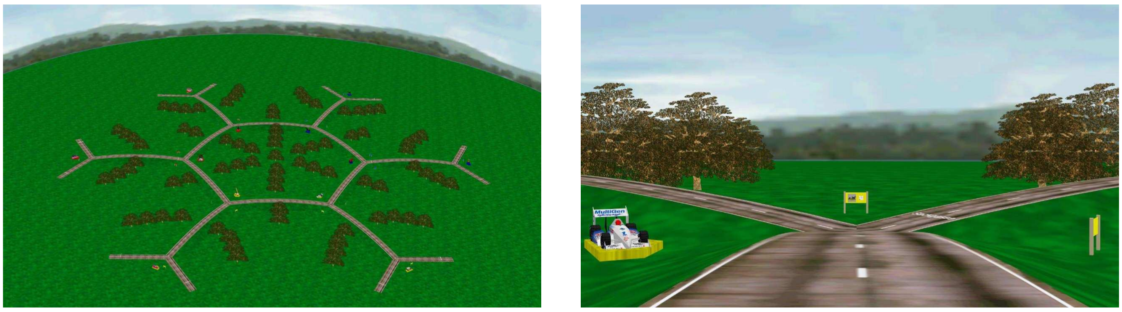

Figure 3.1: left: birds-eye view on the environment; right: subjects view approaching a place with the corresponding landmark

3.1.2 Methods

3.1.2.1 The Virtual Environment

The virtual environment consisted of twelve places that were interconnected by streets. While six places were arranged on a hexagonal ring, the other six places could be reached by dead-end roads starting from the corners of the hexagonal ring (see figure 3.1 and figure 3.2). Each street connected two places within the environment and had a length of 100 meters.

A single landmark was positioned at each place. The landmarks of places on the hexagonal ring were located at the inner-side of the ring, the landmarks specifying places of the dead-end roads were located in the extension of the road (see figure 3.1). While its associated landmarks uniquely specified each place, the places were grouped into three different semantic regions according to the object categories of single landmarks (cars, animals and art objects). A region consisted of two neighboring places within the ring and their associated dead-ends (see figure 3.2). Pilot studies have shown that the spatial clustering of landmarks that belong to the same object category is sufficient to establish regions in subjects' spatial memory.

All streets passed across a hill and crossed a hedge to prevent subjects from seeing from one junction place to any other junction place. Subjects could therefore only perceive the landmarks at their current position.

Subjects navigated through this virtual exhibition park using a computer mouse. By pressing the left and right mouse button they could initiate left/right rotations. When facing a street subjects could move to the next place by hitting the

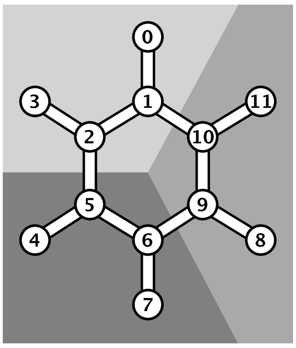

Figure 3.2: Schematic map of the virtual environment. The regions are illustrated as different levels of gray, the places are represented as numbered circles and streets as white lines.

middle button of the mouse. The movements followed a predefined velocity profile. Rotations ended after a 60° turn, translations at the next place.

3.1.2.2 Procedure

After the exploration- and training phase (see chapter 2.2) subjects entered the test-phase. During the test-phase they were repeatedly asked to navigate the shortest possible route connecting their current position with three target places in the environment. The target places were characterized by images of the landmarks associated with these places. The images were superimposed on the projection screen. According to the spatial configuration of starting place and the three target places, the test routes were classified as belonging to one of three route types. Two of the three route types allowed for alternative solutions of equal length (see figure 3.3), and are therefore referred to as symmetric route types (type A and type B). The remaining type was asymmetric allowing for only a single optimal solution (type C). The asymmetric routes were introduced as distractors to impede subjects' learning of the configurations of the symmetric routes. If subjects had learned the geometry of the symmetric routes they could have mastered the navigation tasks without route planning from spatial memory.

By rotating the configuration of start- and target-places by 60° around the center of the environment, six different routes of type A and type B were generated (see table 3.1). By this means, test routes of type A and type B were balanced for left/right movement decisions. Additionally a total of 12 navigation tasks

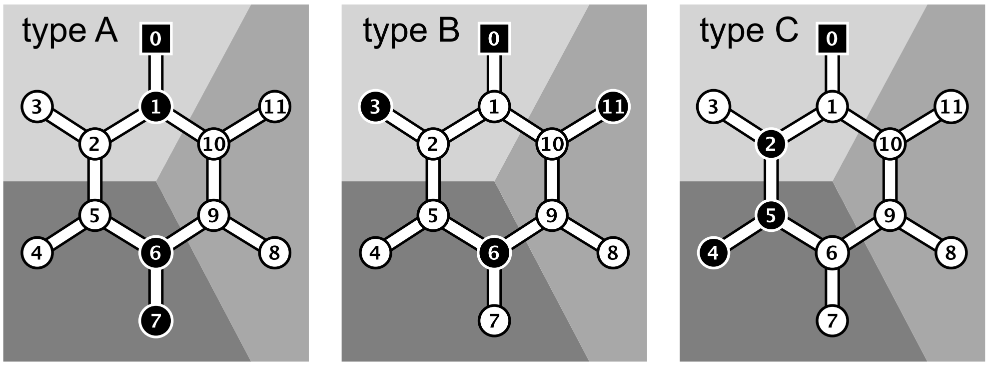

Figure 3.3: The route types (left: type A-, middle: type B-, right: type C-routes). The black squares represent the start places, the black circles represent the goal places. Type A and B navigation tasks (symmetric route types) could be solved on two alternative routes; type A: solution 1: 0,1,2,5,6,7 or solution 2: 0,1,10,9,6,7; type B: solution 1: 0,1,2,3,2,5,6,9,10,11 or solution 2: 0,1,10,11,10,9,6,5,2,3. For routes of Type A solution 1 crossed one region boundary and solution 2 crossed two region boundaries; for routes of type B solution 1 crossed two region boundaries and solution 2 crossed three region boundaries. Type C routes (asymmetric route type) featured only a single optimal solution (0,1,2,5,4).

of type C routes (distractor-routes) were generated (see table 3.1). Subjects navigated all 6 test-routes of type A and type B and 6 routes of type C in each of two blocks, summing up to a total of 18 routes per experimental block. After subjects completed a test-route they were teleported to the start-place of the subsequent test-route, such that they were facing the start-places landmark.

The sequence in which the test routes were presented was pseudo-randomized, such that two successive trials were of different route types. After the test-phase subjects were debriefed. Special interest concerned the question whether or not subjects perceived the different regions that were introduced in the environment.

3.1.2.3 Variable of Interest

As mentioned above, the experiment was designed to investigate the role of environmental regions on human route planning behavior. When navigating the symmetric navigation tasks (type A routes and type B routes) during the test phase, subjects could choose between two alternative optimal routes. While these alternatives were identical with respect to their metric length, they differed in the

Route Type	Start Place (Target Places)
A	0 (1,6,7), 3 (2,9,8), 4 (5,10,11), 7 (6,1,0), 8 (9,2,3), 11 (10,5,4)
B	0 (3,6,11), 3 (4,0,9), 4 (3,7,10), 7 (4,8,1), 8 (7,11,2), 11 (0,8,5)
C	0 (1,10,8), 11 (1,2,3), 8 (9,5,4), 7 (6,9,11), 4 (5,1,0), 3 (5,6,7), 0 (2,5,4), 11 (10,9,7), 8 (9,1,0), 7 (5,2,3), 4 (6,9,8), 3 (2,1,11)

Table 3.1: Here for each route type of the test phase all single navigation tasks are listed. The numbers correspond to the places in the virtual environment (see figure 3.2).

number of region boundaries that had to be crossed. For each subject and each test route type the fraction of route choices passing less region boundaries divided by the total number of correct choices was calculated. If the regions had no influence on human route planning, it was expected that subjects chose between the alternative solutions (crossing less or more region boundaries) with the same frequency. Chance level was therefore 50%. In order to reduce noise, only error free navigations were evaluated, that is, navigations in which subjects found one of the two alternative optimal solutions.

3.1.2.4 Participants

Twenty-five subjects (15 female, 10 male) participated in the experiment, they were paid 8 Euro per hour. Subjects were mostly University students.

3.1.2.5 Statistical Analysis

Data were analyzed using the open source statistics software 'R' (www.r-project.org). The data were obtained in a repeated measures design. With single data points being binary variables, even after pooling across single trials a normal distribution was not given. Therefore the non-parametric Wilcoxon's signed rank test was applied to the data when comparing to a given chance level and the Wilcoxon rank sum test was applied for comparison between groups. Using the 'exactRankTests'-package for R it was corrected for ties (available from: http://cran.au.r-project.org).

The error-bars of all data plots in this experiment display standard errors of the mean (s.e.m.).

3.1.3 Results

Training Routes. If a training route was not completed using the shortest possible route, the trial was recorded as an error, and the training route was repeated. On average subjects made 2.84 errors during training. Male subjects produced 2.15 errors, while female subjects produced 3.58 errors on average (Wilcox rank sum test: p=.27).

Test Routes. After the experiment subjects were debriefed. 21 out of 25 subjects reported that they had recognized the regions that were introduced in the environment. The remaining four subjects insisted that they had not perceived the car-, animal- and art-region in the environment. These two subject groups (group 'reported' & group 'not-reported') were evaluated independently.

Even though subjects from the 'reported' group performed error-free navigations in 78.2 % of all test-navigations, and subjects from the 'not-reported' group performed error-free navigations in only 54.9 % of the test-navigations (see figure 3.5), the difference did not reach statistical significance (Wilcoxon rank sum test: p=.09).

By evaluating the symmetric test-routes (type A- and type B-routes), subjects' overall preference to minimize the number of region boundaries crossed along a symmetric route was analyzed. A Wilcoxon Rank Sum Test revealed a significant difference between the 'reported' and 'not-reported group' (Wilcoxon rank sum test: p<.01; see figure 3.5). While the subjects of the 'not-reported'-group performed at chance level (Wilcoxon signed rank test: 42.9% against chance level (50%), p=.5), subjects of the 'reported'-group significantly preferred routes that crossed fewer region boundaries (67.1% against chance level (50%), p<.001). Subjects who had not recognized the regions within the environment did not show a 'region effect' and were therefore disregarded from the rest of the analysis.

A comparison between female and male subjects did not reveal a significant difference between genders. While female subjects (n=11) chose the route crossing less region boundaries in 66% of the test-navigations, male subjects (n=10) chose

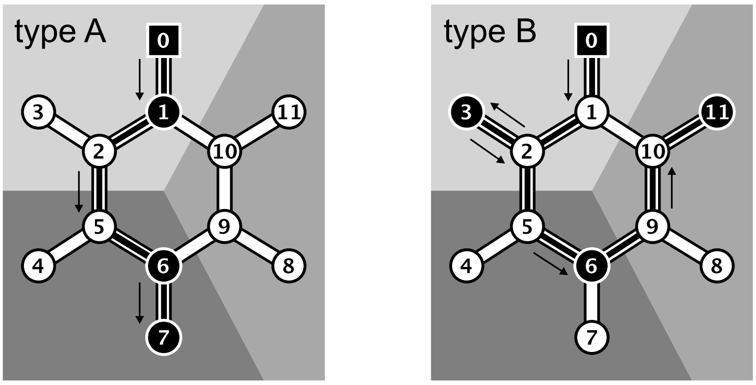

Figure 3.4: Here subjects' preferred paths for navigation tasks of type A routes (left) and type B routes (right) are superimposed on the schematic drawings of the virtual environment (the arrows indicate subjects' direction of movement). The black squares represent the start places, the black circles represent the goal places.

the route crossing less region boundaries in 68.3% (Exact Wilcoxon rank sum test: p=.69).

The symmetric routes of the test phase could be subdivided into two route types (see figure 3.3: type A- and B-routes), that mainly differed in the overall length. Subjects' preference for routes that crossed fewer region boundaries did not differ between type A routes and type B routes (type A: 64.9%, type B: 70.6%, Wilcoxon rank sum test: p=.44, see figure 3.6). For both of the symmetric route types (type A- and type B-routes) subjects showed a significant preference for paths that crossed fewer region boundaries (type A: Wilcoxon signed rank test: 64.9% against chance level (50%), p=.009; type B: Wilcoxon signed rank test: 70.6% against chance level (50%), p<.001; see figure 3.4 and 3.6).

In the second experimental block of the test phase, subjects tended to show an increased preference for routes that crossed less region boundaries, still this trend did not reach statistical significance (block 1: 61.6%, block 2: 71.7%, Exact Wilcoxon rank sum test: p=.12, see figure 3.6).

3.1.4 Discussion

Subjects who had recognized the semantic regions within the environment, preferentially navigated routes that crossed fewer rather than more region bound-

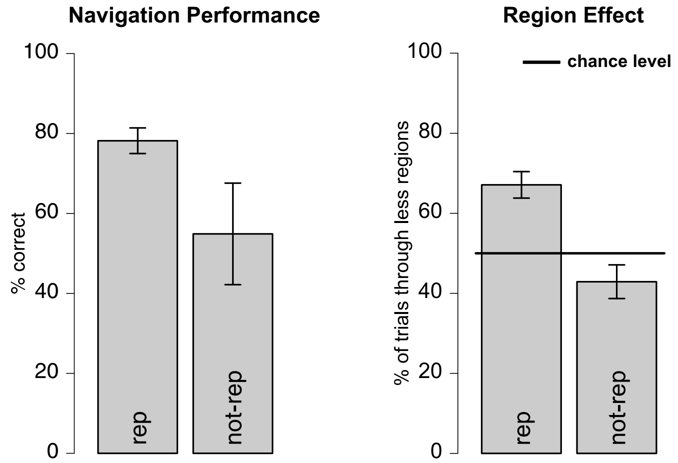

Figure 3.5: left: subjects' overall performance during the test phase for the 'reported' (n=21) and 'not reported' group (n=4); right: subjects' preference for paths that crossed fewer region boundaries when navigating symmetric routes (type A- and type B routes) for the 'reported' and 'not reported' group.

aries. This effect reveals an influence of environmental regions on human route planning behavior. A possible explanation for the observed region-effect could be given by subjects' uncertainty about the positions of the places within the environment. Note that in this experimental environment, routes that crossed fewer region boundaries did also pass by more places that reside in goal regions. If subjects had knowledge about the positions of the regions but not about the exact positions of the places within the regions, they could increase the chance of finding a target place accidentally by navigating routes that touched on more places in the goal region (that is to say, routes that crossed fewer region boundaries). This explanation suggests that the region-effect should be reduced by prolonged learning. If anything, the data suggests a trend to the contrary.

Bailenson et al. (1998) have formulated the 'road climbing' principle, stating that subjects plan their routes in order to leave the region containing the origin as fast as possible. Contrary to our results, this strategy predicts that subjects chose the route crossing more rather than fewer region boundaries when navigating routes of type A (see figure 3.3). The data therefore does not support the 'road climbing' principle.

Since subjects could only perceive the landmark at their current position, all information necessary to plan the routes and all information responsible for the observed region-effect had to be obtained from memory. The regions must therefore

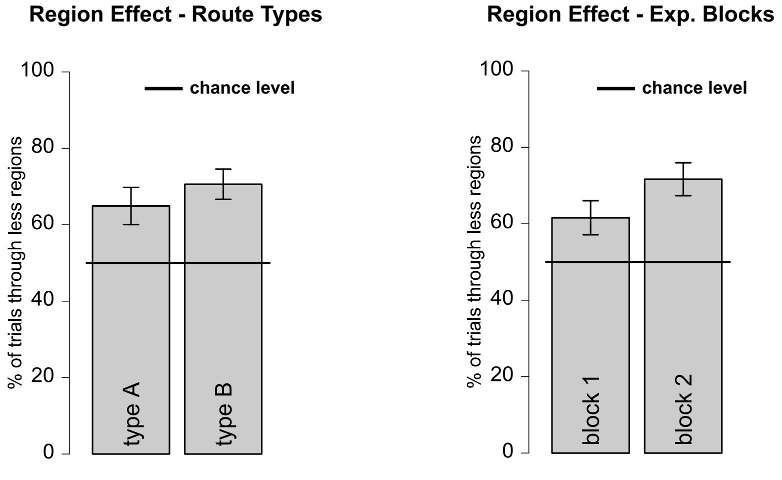

Figure 3.6: left: subjects' preference for routes that crossed fewer region boundaries for type A and type B routes (collapsed over experimental blocks); right: subjects' preference for routes that crossed fewer region boundaries for the experimental blocks (collapsed over type A and B routes).

be represented in spatial memory. It remains an open question of how environmental regions are represented in spatial memory, and whether these regions act on the planning mechanism itself. Below three possible hypotheses (H1 - H3) or planning strategies, respectively, that could have accounted for the observed region effect are discussed.

H1 - Distorted Representation. Multiple experiments have shown that regions within an environment distort distance estimations (see chapter 1). While distances of locations within the same region are systematically underestimated, distances between locations in different regions are systematically overestimated. If such systematic distortions were encoded in spatial memory, streets that crossed region boundaries would be over-represented as compared to streets that did not cross a region boundary. Therefore routes that crossed fewer region boundaries would have appeared shorter than routes that crossed more region boundaries. More generally speaking, crossing a region boundary imposes a cost on the system.

H2 - Persistence. Subjects tend to stay in their current region as long as possible. When navigating the symmetric test routes this would have implicitly resulted in a preference for routes that crossed fewer region boundaries. Such a persistence strategy could result from spatial priming. McNamara (1986) has shown stronger priming between locations in the same region as compared to locations that reside in different regions. A hypothetical planning mechanism that spreads activation through the neural substrate of spatial memory until reaching the target location would therefore at first find routes that switch fewer rather than more regions.

***H3* - *Hierarchical Planning*.** This hypothesis states that regions are explicitly represented in the hierarchical representation of space. In routes with multiple goals, the planning algorithm will start by selecting the next goal location. If the next goal resides in a distant region, the algorithm will plan a route for fastest access to that region, irrespective of where exactly the goal is located within that region. Such a planning mechanism makes use of the hierarchical structure of spatial memory and would lead to results like the ones presented.

These three strategies do result in different requirements on the spatial representation and the planning strategy. While environmental regions have to be explicitly represented in spatial memory for the *Persistence-* and the *Hierarchical Plannin*g - hypothesis, distortions of the memorized distances between places would account for the *Distorted Representation* - hypothesis. In experiment 2 data is presented that allows to distinguish between the different hypothesis.

3.2 Experiment 2

3.2.1 Purpose

In experiment 1 an influence of regions within an environment on human route planning behavior could be shown. Subjects preferred routes that crossed fewer region boundaries rather than alternative routes of equal length. Three navigation strategies have been discussed that could account for the observed effect. Experiment 2 was designed to discriminate between the three strategies, as explained below.

3.2.2 Methods

3.2.2.1 The Virtual Environment

The virtual environment consisted of two islands containing six places each. The places were interconnected by roads within each island and by bridges between the islands (see figure 3.7 and figure 3.8). While three places of each island were located at the riverside (riverside places: 3, 4, 5, 6, 7, 8; see figure 3.8) the remaining places were located at the oceanside (oceanside places: 0, 1, 2, 9, 10, 11; see figure 3.8). Each place could be identified by an associated, unique landmark. While the landmarks of one island were all cars, the landmarks of the other island were of the category animals. This clustering of landmarks belonging to the same category, as well as the existence of two separated islands, defines two regions within the environment and should therefore establish region representations in subjects' spatial memory of the environment.

Landmarks were only visible when subjects were in close proximity, i.e. at the corresponding place, and are therefore referred to as pop-up landmarks. While subjects could visually perceive the streets, islands and places, they could only see one landmark at a time.

3.2.2.2 Procedure

After the exploration- and training-phase (see section 2.2) subjects entered the test-phase. During the test phase, subjects were asked to navigate the shortest

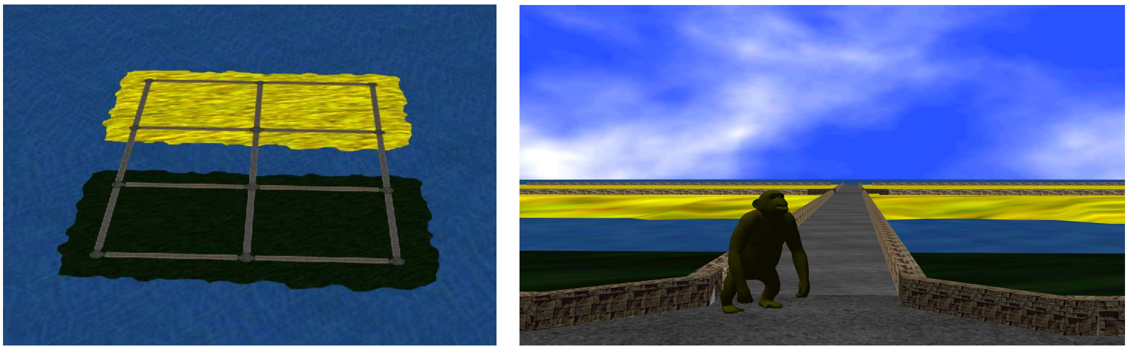

Figure 3.7: left: bird's eye view of the experimental environment; right: subject's perspective with a pop-up-landmark (ape).

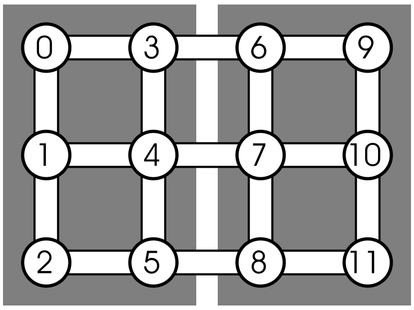

Figure 3.8: Schematic map of the experimental environment. Places are displayed as numbered circles, streets and bridges are represented by lines, the gray rectangles represent the islands or regions, respectively.

possible route from a given starting place to a single target place. The target place was characterized by an image of the landmark associated with that target place. The image was superimposed on the screen. According to the spatial configuration of start-place and target-place, each navigation task could be assigned to one of six route-types. Additionally, the route types could be classified as belonging to either the square test-routes (see figure 3.9) or the rectangular test-routes (see figure 3.10).

Multiple routes of each route type were generated by mirroring the specific configuration along the horizontal, the vertical or both center lines of the environment or by shifting start- and target place on the street grid. Subjects navigated four routes of each route type in each of two experimental blocks, adding up to a total of 48 test routes (see table 3.2 for detailed descriptions of the test routes).

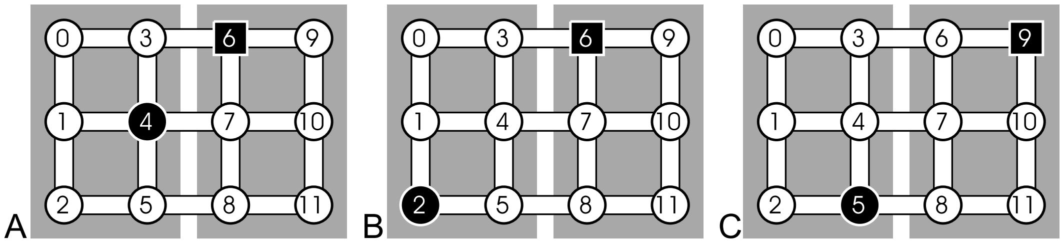

Figure 3.9: The square test-routes. The black square and circle represent start- and target-place, respectively. The square routes could be classified as short routes (type A) and long routes (type B and C). Type B and type C routes differed in the distance of starting and goal place from the region boundary.

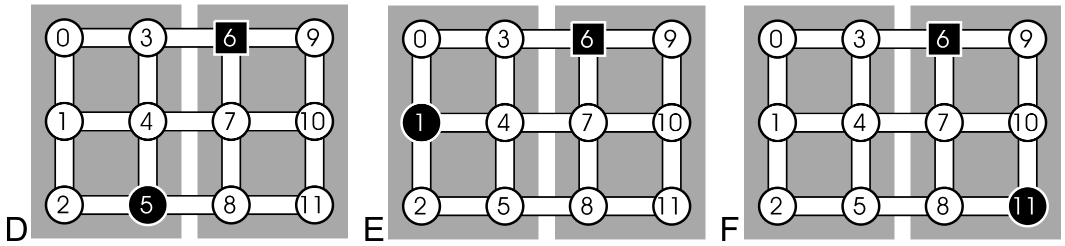

Figure 3.10: The rectangular test-routes. The black square and circle represent start- and target-place, respectively. While type D and type E routes both crossed the region boundary, type F routes stayed within a region. Type D and type E routes differed in the orientation of the long side with respect to the region boundary.

After subjects completed a test route they were teleported to the start-place of the subsequent test-route. For each route at least two optimal solutions were possible, whose initial directions differed by 90°. The initial heading of the subjects was in the middle of the route alternatives which therefore appeared at visual angles 45° left and 45° right.

3.2.2.3 Predictions & Variable of Interest

The hypotheses discussed in section 3.1.4 lead to different predictions for the navigation behavior in the current experiment. All route types in which subjects had to cross the region boundary did in principle discriminate between the different strategies, as explained below.

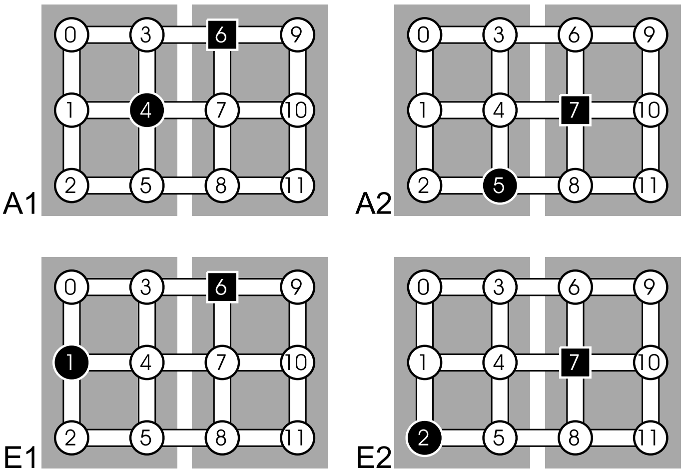

Figure 3.11: The variants of type A and type E routes. By shifting the start and target places about one grid point, variants of type A and type E routes with the same spatial configuration of start place and target places but different absolute positions were created. The number of possible movement decision along the routes were less for routes of type A1 and type E1 as compared to routes of type A2 and E2. The variants of type A and type B routes were created to control for possible border effects.

Route Type	Start Place → Target Place
A	8→4, 4→6, 3→7, 7→5, 4→8, 7→3, 6→4, 5→7
B	8→0, 5→9, 6→2, 3→11
C	2→6, 9→5, 0→8, 11→3
D	3→8, 5→6, 6→5, 8→3
E	7→2, 8→1, 4→9, 3→10, 4→11, 7→0, 6→1, 5→10
F	3→2, 9→8, 0→5, 6→11, 8→9, 2→3, 5→0, 11→6

Table 3.2: Here for each route type all single test routes are listed. The numbers correspond to the places in the virtual environment (see figure 3.8). Note that type B, type C and type D routes provided 4 test routes only, that were repeated in each of the two experimental blocks.

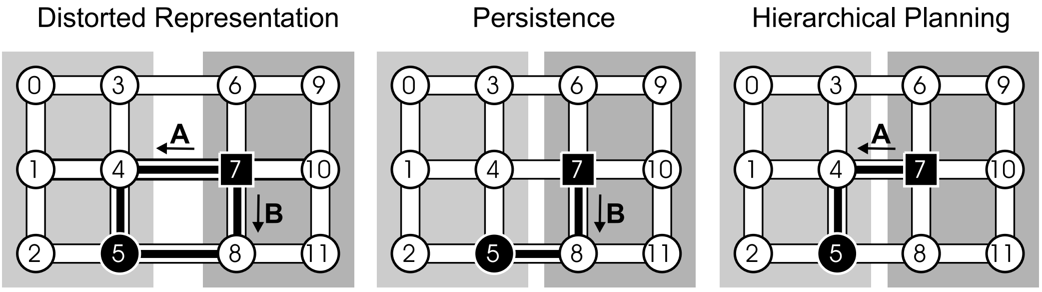

Figure 3.12: left: the Distorted Representation-hypothesis predicted that subjects chose to cross the region boundary sooner rather than later in 50% of the navigations; middle: the Persistence-hypothesis predicted that subjects stay in the starting region as long as possible; right: the Hierarchical Planning hypothesis predicted that subjects approach the target on the route that allowed for fastest access to the target region.

H1* - *Distorted Representation. The 'Distorted Representation' hypothesis did not predict any systematic effect. Since subjects had to cross only one region boundary on all optimal alternative paths, an over-represented region boundary did not result in alternative paths with different length. This is in contrast to experiment 1, in which the alternative paths crossed different numbers of region boundaries. The 'Distorted Representation' hypothesis predicted that subjects chose to cross the region boundary sooner rather than later in 50% of the navigations (see figure 3.12).

H2* - *Persistence. The Persistence strategy predicted that subjects stay in their current region as long as possible. That is to say, the 'Persistence' strategy stated that subjects preferred routes that allowed to avoid the crossing of region boundaries as long as possible (see figure 3.12).

H3* - *Hierarchical Planning. The *Hierarchical Planning* hypothesis proposed that subjects plan towards the target region rather than towards the target place. Not until entering the target region did subjects plan the rest of the route. This strategy predicted that subjects approached the target on the path that allowed for fastest access to the target region (see figure 3.12).

Variable of Interest. As pointed out above, the different strategies predicted different navigation behavior with respect to subjects' approach to the region containing the target place. Each route allowed for at least two alternative optimal solutions. For each subject and for each route type that crossed a region boundary, subjects' preference to approach the target region as fast as possible, by choosing the alternative that allowed to enter the target region sooner rather than later, was evaluated.

3.2.2.4 Participants

Thirty subjects (14 female, 16 male) participated in the experiment, they were paid 8 Euro an hour. Subjects were mostly University students.

3.2.2.5 Statistical Analysis

See section 3.1.2.5.

3.2.3 Results

Training Routes. If a training route was not completed using one of the shortest possible routes, the trial was recorded as an error, and the training route was repeated. On average subjects made 2.2 errors during the training phase. Male subjects produced less errors than females when navigating the 6 training routes (females: 3.21 errors; males: 1.25 errors; Wilcox rank sum test: p=.028).

3.2.3.1 Test Routes

Performance. All route types allowed for at least two alternative optimal solutions. In 92.8 % of the test-navigations subjects performed error free navigations, that is to say they have found one of the alternative optimal paths. While female subjects navigated correctly in 90% of the trials, male subjects reached 95.3% correct navigations (Wilcox rank sum test: p=.08). In order to reduce noise only error-free navigations were evaluated.

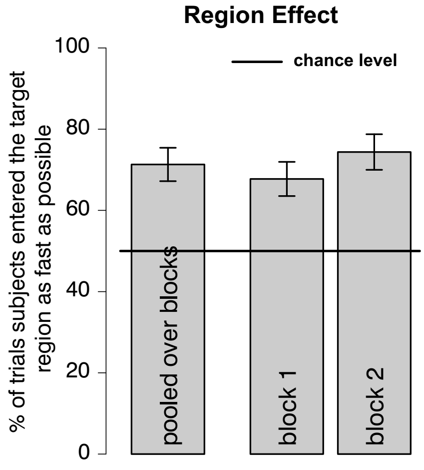

Figure 3.13: Subjects' preference to enter the target region sooner rather than later for all route types with starting place and target place in different regions (type A,B,C,D,E routes). The left bar displays subjects' preference pooled over experimental blocks, while the remaining bars display subjects' preference for the experimental blocks separately.

Regions Effects. By pooling across type A,B,C,D and E routes (see figure 3.9 and figure 3.10), for all route types with starting- and target-places in different regions, it was evaluated, how often subjects chose the alternative that allowed for fastest access to the target region. Subjects chose the path that allowed for fastest access to the target region in 71.3 percent of the navigations (Wilcoxon signed rank test against 50%: p=.0001, see figure 3.13). During the first test-block, subjects chose to enter the target region sooner rather than later in 67.7% of the trials, during the second test-block they did so in 74.4% of the trials (Wilcox rank sum test: p=.11, see figure 3.13). Female and male subjects did not differ in their preference for routes that allowed for fastest access to the target region (males 71.4%, females 71.2%, Wilcox rank sum test: p=.94).

Rectangular Test Routes. In contrast to the square test routes, the rectangular test routes had sides with different length (see figure 3.10). Since type F routes did not cross the region boundary, they allowed to separate a possible influence of the rectangular shape on route planning from any region effects. It was evaluated whether subjects showed a preference to first navigate the long leg or the short leg, respectively (see figure 3.15). With their first movement decision subjects followed the long leg of the route in 54.1 % of the navigations (Wilcoxon signed rank test against chance level (50%): p=.35). That is to say, a systematic influence

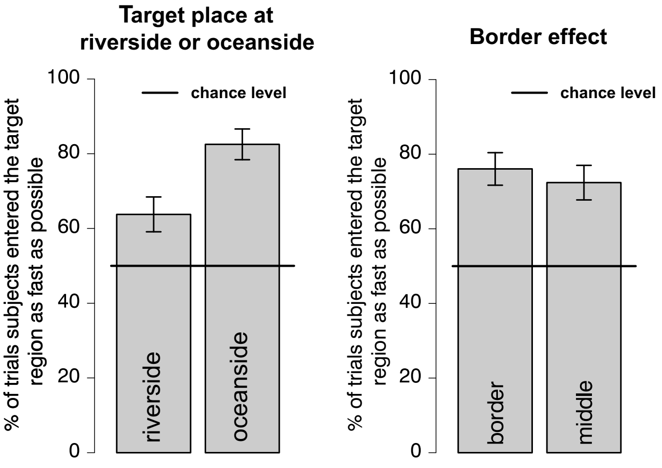

Figure 3.14: left: Subjects' preference to enter the target region sooner rather than later for routes with target places at the riverside and at the oceanside; right: Subjects' preference to enter the target region sooner rather than later for routes with starting places at the border of the environment or with starting places within the environment.

of the rectangular shape of type F routes on human route planning was not found.

Routes with Targets at the Riverside vs Targets at the Oceanside. Irrespective of the rectangular or square shape of the navigation tasks, the test routes could be divided into routes that had the target place located at the riverside (target place was 3, 4, 5, 6, 7 or 8; see type A, C and D routes in figure 3.9 or figure 3.10, respectively) and routes that had the target place at the oceanside of the environment (target place was 0, 1, 2, 9, 10 or 11; see type B and E routes in figure 3.9 or figure 3.10, respectively). Subjects' preference to enter the target region sooner rather than later differed between these categories of routes (target at riverside: 63.8%, target at oceanside: 82.5%, Exact Wilcox rank sum test: p<.001, see figure 3.14), subjects clearly showed a stronger preference in routes with the target at the oceanside as compared to routes with the target at the riverside. Still for both of the subgroups of routes (target at riverside, target at oceanside) subjects showed a significant preference for routes that allowed for fastest access to the target region (Wilcoxon signed rank test against 50%: p<.01 and p<.001, respectively).

Border Effects. A comparison of the two optimal solutions of type A1 routes (see figure 3.11) shows a striking difference between these alternatives. The route

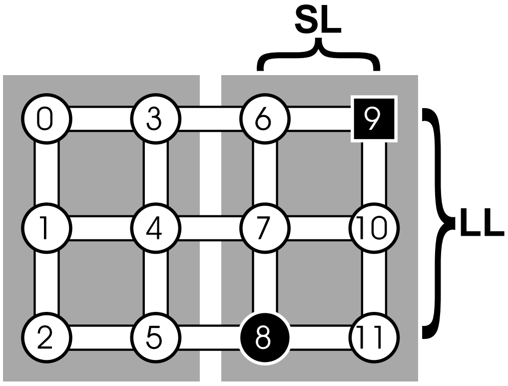

Figure 3.15: The rectangular type F routes did not cross the region border (LL = long leg, SL = short leg). From the starting place (place 9), subjects could decide to go to place 10 (following the long leg) or to go to place 6 (following the short leg).

along the the border of the environment (along the places 6,3,4) provided less possible movement decisions than the alternative solution (along the places 6,7,4). This difference resulted from the T-junction at the border place 3 as compared to the X-junction at place 7. While a T-junction at the most allows for three possible movement directions, a X-junction allows for four movement decisions. One might argue that this difference results in routes with different complexity. If subjects took the complexity of alternative routes into account during route planning, they might have preferred routes along the border. This 'border effect' would in fact add up to the observed region effects in some of the test routes. By comparing subjects' navigation strategies of routes of type A1 and type E1 against routes of type A2 and type E2 (see figure 3.11), this possible border effect was separated from the region effect. Subjects preferred routes that allowed for fastest access to the target region in 76.1% of the navigations in routes of type A1 and E1, they did so in 72.4% of the navigation in routes of type A2 and E2 (Wilcox rank sum test: p=.46, see figure 3.14). No reliable influence of routes with different complexity on route planning behavior was found in this experiment.

3.2.4 Discussion

When navigating routes with starting place and target place in different regions, subjects reliably preferred routes that allowed for fastest access to the target region above alternative routes. The border of the virtual environment or the different complexity of alternative routes, respectively, had not influenced subjects' navigation behavior. Also additional strategies like the Initial Segment Strategy (Bailenson et al., 2000) could not account for the results. The Initial Segment Strategy (ISS) states that subjects prefer routes with the longest initial straight segment above alternative routes. Contrary to our results, the ISS predicts that subjects preferred to first navigate the long leg rather than the short leg on the rectangular routes.

Having ruled out these navigation strategies, it is concluded that the observed effect is indeed due to the regions that were introduced in the environment. The results of experiment 2 are in line with the predictions for the *Hierarchical Planning*-hypothesis (H3), while they contradict the *Distorted Representation-* (H1) and *Persistence*-hypothesis (H2). The *Hierarchical Planning*-hypothesis predicted that subjects chose a target region first, and then planned their route in order to access that target-region as fast as possible (see section 3.2.2.3). Such a planning algorithm would lead to the navigation behavior observed during the experiment.

Depending on the position of the target place in the target-region the magnitude of the 'region effect' was modulated. If the target was located at the riverside the effect was substantially smaller as compared to navigations with the target at the oceanside of the environment. This modulation might reflect the different characteristics of places at the region border (riverside) and the remaining places (oceanside). In the virtual environment all places at the region border were also transits to the other region. In more complex environments in which one has to plan routes that pass through multiple regions, it can be important to also plan where to enter and where to leave regions. The entrances and exits of regions might therefore be represented specifically, e.g., by explicitly representing the spatial relation of the places that create transits between regions. This kind of information would allow for a navigation strategy that could modulate the described 'region-effect'. In addition to planning towards the target region, subjects could also plan towards the transit that allowed for direct transfer to the target place. This might explain the weaker effect found for routes with targets at the riverside.

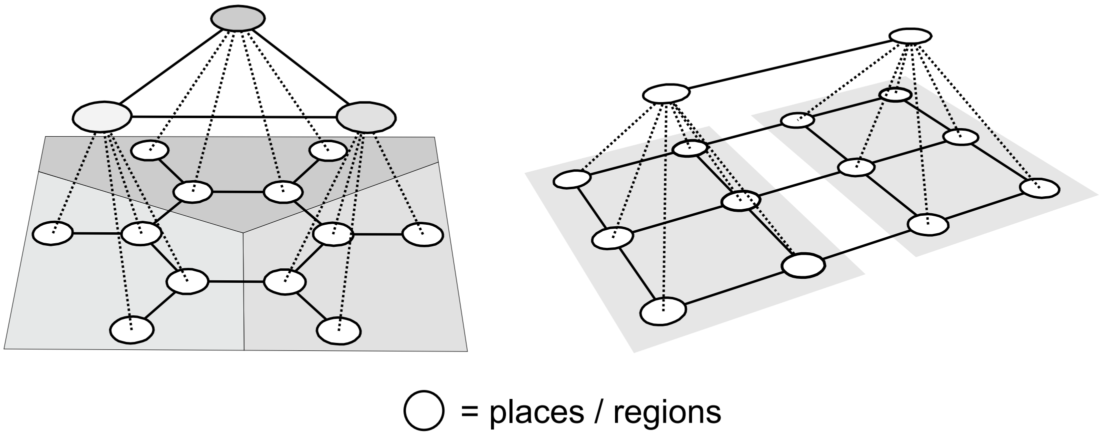

Figure 3.16: The hierarchically organized reference memory of the virtual environments used in experiment 1 (left) and in experiment 2 (right).

3.3 General Discussion of Experiment 1 & Experiment 2

Experiment 1 and experiment 2 revealed an influence of environmental regions on human route planning and navigation behavior. In experiment 1 it was shown that subjects minimized the numbers of region boundaries they passed by during a navigation. Three alternative hypotheses that could account for the observed effect were offered. Experiment 2 was designed to discriminate between these hypotheses and showed that subjects entered regions containing a target place sooner rather than later. Results from both experiments were consistent with the *Hierarchical Planning*-hypothesis (H3) only. According to this hypothesis human route planning takes into account region connectivity, and is not based on place connectivity alone. This requires environmental regions and spatial relations among these regions to be explicitly represented in human spatial memory.

This requirement is in line with hierarchical theories of spatial representations. According to these theories, places are grouped together to regions which form higher level nodes in a graph-like representation of space. Spatial relations among regions can then be represented at the region level. Figure 3.16 represents such a hierarchical reference memory for the virtual environments used in experiment 1 and in experiment 2.

It should be noted at this point that the environments that were used for the experiments consisted of clear cut regions. In real world environments region boundaries are usually vaguely defined, as recently pointed out by Montello, Goodchild, Gottsegen, & Fohl (2003). Additionally, regions as represented in spatial memory might overlap. For the analysis it was assumed that subjects represented the regions that were introduced in the environments as such in their spatial memory. Indeed most subjects in experiment 1 and all subjects in experiment 2 reported during the debriefing sessions that they had perceived the regions within the virtual environments; subjects who did not perceive the different regions in experiment 1 did not show any 'region effect'. However, it can not be ruled out, that subjects represented the regions somewhat differently.

In the next chapter hierarchical planning schemes, i.e. planning algorithms that make use of the hierarchical structure of representations of space, are introduced and discussed with respect to the findings described in this chapter. Also a new hierarchical route planning algorithm, the *fine-to-coarse* planning heuristic, is developed and introduced. The *fine-to-coarse* planning heuristic is a cognitive model of region-based route planning that constitutes an alternative to other hierarchical planning algorithms.

Chapter 4

A Cognitive Model of Region-based Route Planning

4.1 Hierarchical Route Planning - The Basic Concept

Finding the shortest, the cheapest, the most reliable or simply a reasonably short path between one or many pairs of nodes in a network is a problem that is not restricted to navigation and route planning in humans, but arises in various disciplines. Typical examples are routing in transportation and communication networks and applications like geographic information systems (GIS). Although numerous algorithms have been developed to solve the shortest path problem, even with state-of-the-art computers these algorithms are often inefficient due to the growing size of the underlying networks. To overcome these problems *hierarchical planning* algorithms have been developed.

Hierarchical route planning algorithms usually apply hierarchies in order to partition a base graph that represents an environment into less complex graphs, that constitute abstractions of the base graph. Planning in such graphs is always a trade off between planning costs and the quality of the solution. That is to say, while hierarchical planning algorithm reduce memory load as well as computation effort during route planning, they do not guarantee to find the optimal solution for a given navigation task. However, a good hierarchical planning algorithm greatly reduces the costs during route planning, while the resulting solutions are near-optimal.

In the following section a number of hierarchical route planning schemes are introduced that have been derived from computational models of human spatial memory and cognition.

4.2 Examples for Hierarchical Route Planning Schemes

The Traveller. The *Traveller* is a cognitively based computer model that simulates learning and problem solving in spatial network (Leiser & Zilbershatz, 1989). The *Traveller* learns an environment by exploration and by memorizing local connections between locations, i.e. what node is reached from what other node by what action. These condition-action pairs are the basic components of the model; sequences of such condition-action pairs are used to represent routes. New routes are found by an mechanism comparable to spreading activation. The *Traveller* scans all nodes accessible from the start node to see if the target node is included. If the target was not reached, the *Traveller* scans all nodes accessible from the nodes that had already been scanned to see if the target node is included. This procedure is iterated until the target node is reached and the route is found. Routes that have been planned and executed are remembered by the *Traveller*. When planning new routes, existing knowledge, i.e. formerly planned routes, is used. By this means the knowledge the *Traveller* assembles over time relies on its experience.

In *Traveller* often visited and well known nodes become so-called centroids[1]. The existence of such centroids allows to decompose the planning of a route into three sub-problems: (i.) from the start location to the closest centroid; (ii.) from this centroid to a second centroid that is close to the target node; and (iii.) from the second centroid to the target node. Since the search for a new route is interrupted as soon as the first centroid is found, the Traveller will learn many routes towards this centroid. Over time the *Traveller* will build up a representation of space that consists of different draining areas (regions), each of which has its own centroid. Such a representation of space incorporates an abstraction level, i.e. the

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[1] Note that this is not the standard definition of a centroid

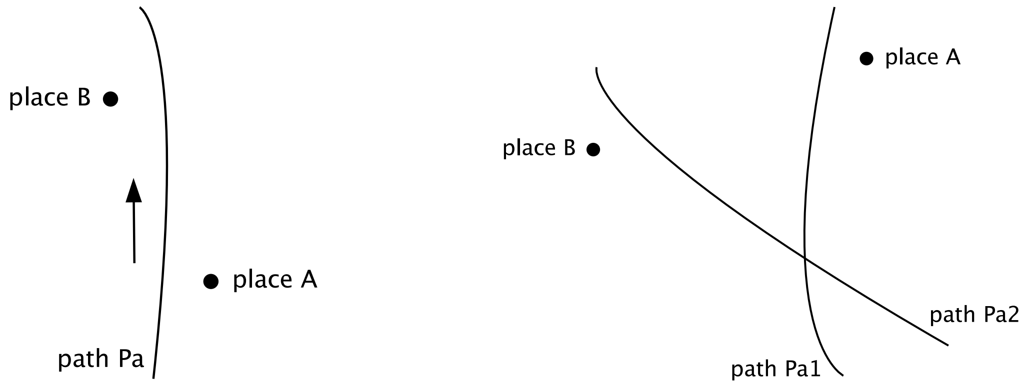

Figure 4.1: Planning routes from place *A* to place *B* using boundary relations; left: The path *Pa* shares a boundary relation with place *A* as well as place *B*, therefore path *Pa* becomes a subgoal and the planning task is refined to the search for a route from place *A* to path *Pa* and from path *Pa* to place *B*; right: Place *A* and place *B* do not share boundary relations with the same path. Place *A* shares a boundary relation with path *Pa1* and place *B* shares a boundary relation with path *Pa*2, therefore the subgoal of finding a connection between path *Pa1* and path *Pa2* is proposed.

regions, that is used during route planning in order to decompose the planning task, therefore reducing computational effort.

"The skeleton in the cognitive map". Kuipers, Tecuci, & Stankiewicz (2003) have proposed a route planning scheme that is mainly based on a 'skeleton', i.e. a subset of major paths. In this model an environment is represented by the means of a topological map, a bipartite graph with a set of nodes corresponding to places and a set of nodes corresponding to paths between places. Assuming that paths extend to infinity, a single path will divide the places within the environment in three subtypes, places on the path, places left to the path and places right to the path. Such relations are called boundary relations and are used during route planning as follows: (i.) if a route has to be planned in order to get from place *A* to place *B*, and (ii.) if there is a path *Pa* such that place *A* is right of *Pa* and place *B* is left of *Pa*, then (iii.) path *Pa* becomes a subgoal, and the route planning task is refined to the search for a route (iv.) from place *A* to *Pa* and (v.) from *Pa* to place *B* (see figure 4.1).

Kuipers et al. also proposed a positive feedback cycle between the inference of boundary relations and the impact of boundary relations on the wayfinding process. The feedback cycle works as follows: traveling along a path *Pa* makes it likely that boundary relations of path *Pa* and other places are inferred; the existence of boundary relations between a path and some place increases the chance that the corresponding path is used during wayfinding; traveling this path increases the probability that new boundary relations are inferred. By the means of this self-reinforcing process a 'skeleton' of paths rich in boundary relations emerges. This 'skeleton' is a subset of all paths and constitutes an abstraction of the base graph that implicitly reduces computational effort during route planning, since wayfinding most easily finds routes using paths of the skeleton.

PLAN. PLAN is a computational theory of cognitive mapping (Chown et al., 1995), i.e. of how humans learn and represent large-scale environments. PLAN consists of an associative network of landmarks, based on NAPS (Network Activity Passing System, Levenick (1991)), in which nodes correspond to landmarks, connections between two nodes represent the ability to move between two landmarks. Two landmarks only become connected if one is visible from the other, that is to say all information stored in this system is local information. The strength of a connection between two landmarks is adapted according to the familiarity, i.e. the number of times this connections has been traveled. Again, in such an associative network routes can be extracted by spreading activation, connections with high strength will propagate more activation that connections with low strength. Therefore familiar routes will be chosen over new routes, even if the familiar routes are suboptimal.

While the described network of local landmarks is purely topological, Chown et al. add a second component that provides local directional information, the so-called *local maps*. The *local maps* are created at choice points, and store the corresponding visual scene by the means of landmarks and directions to these landmarks. Again, *local maps* are organized in an associative network.

Additionally Chown et al. introduce so-called *regional maps*. Regions within these maps are defined by visual barriers and by *gateways*. *Gateways* are transitions between spaces or regions, in buildings gateways typically refer to doorways. Regional maps are basically survey maps that have the same basic structure as the local maps, but provide a coarse structure of the environment. Each region is represented by a single landmark. Regional maps are primarily used during route planning. First a coarse route plan is generated using the coarse spatial information provided by the regional map. Plans formed at this levels are simple and easy to compute and they usually rule out a large number of sub-optimal paths. However, route plans formed at high abstraction levels do not provide detailed instructions, as needed when making movement decisions at choice points. Therefore each step of a coarse plan has to be broken down and a fine route plan that allows for navigation has to be generated and remembered until the next point of the coarse route plan has been reached.

Such a planning scheme, in which the hierarchies in representations of space are used to first generate coarse route plans that are successively refined, is usually referred to as **coarse-to-fine** route planning. While *coarse-to-fine* planning algorithms are consistent with the data of Experiment 1 and Experiment 2, neither the *Traveller* (Leiser & Zilbershatz, 1989) nor a ’skeleton’ in the spatial representation (Kuipers et al., 2003) could account for the empirical finding. In both, the *Traveller* and in the ’skeleton’ based navigation scheme, it had to be expected that subjects navigated on the same routes in all navigation tasks, either because they always visited the same centroids, or because they always used the same paths in the ’skeleton’.

4.3 The *fine-to-coarse* Planning Heuristic[2]

Coarse-to-fine route planning algorithms assume that a complete plan, however coarse, is generated at the beginning of a travel, that it is then stored in memory, and that it is eventually executed step by step. Such algorithms have a large memory load while the processing effort is rather low. However, if it is assumed that processing may go on with navigation, an algorithm with low memory load and higher processing load would appear rather more attractive. Here an alternative model is introduced that plans steps only one at a time and that minimizes memory load. The algorithm relies on a working memory stage containing a detailed representation of the current position and a coarse representation of distant locations. It is therefore called the ***fine-to-coarse*** planning heuristic.

In contrast to *coarse-to-fine* algorithms, the *fine-to-coarse* planning heuristic uses different hierarchical levels of spatial memory simultaneously rather than successively during route planning. This is achieved by planning the route in a representation that uses fine-space information for close locations exclusively and

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[2] Heuristics are rules of thumb, simplifications, or educated guesses that reduce or limit the search for solutions in domains that are difficult and poorly understood. Unlike algorithms, heuristics do not guarantee optimal solutions. For an extensive overview of the use of heuristics in human decision making see Gigerenzer, Todd, & the ABC research Group (1999).

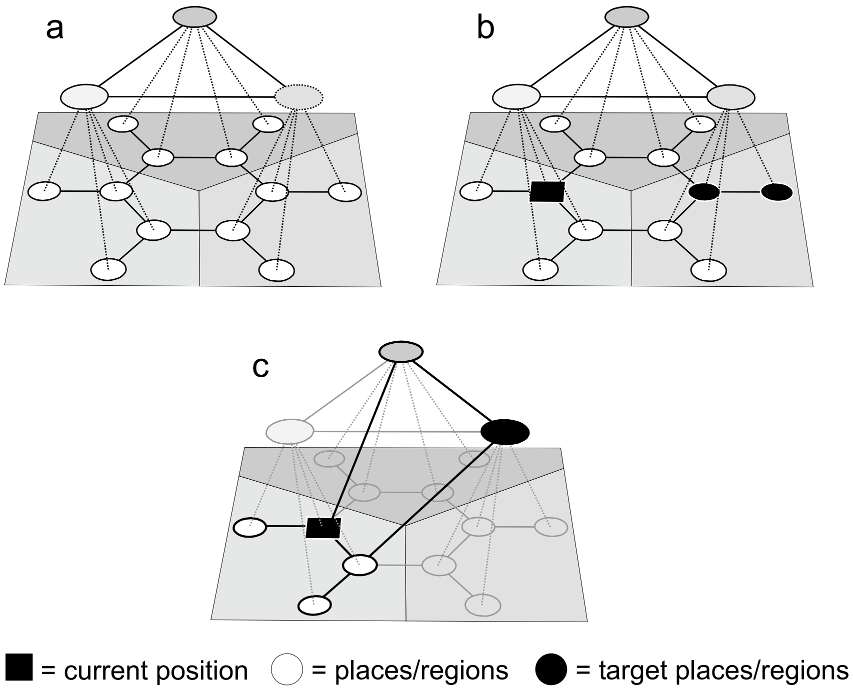


Figure 4.2: Generating a focal representation from hierarchical reference memory, current ego-position and targets: Illustration *a* represents the hierarchically organized reference memory of the virtual environment used in experiment 1. In illustration *b* an observer (black rectangle) is placed at a certain position within the environment, also target places are superimposed on the reference memory. Illustration *c* demonstrates the corresponding focal representation, that uses different levels of detail for close and distant places. Black circled nodes and black edges represent the active part of the representation. Distant places are represented by their super-ordinate spatial entities, while only close places, i.e. places within the current regions, are represented at the finest resolution. The transitions from places in one region to adjacent regions either have to be represented in the hierarchical reference memory or have to be created when the focal representation is generated in working memory.

coarse-space information for distant locations exclusively. Such representations are referred to as *focal representations*. The *focal representation* is a working memory stage, generated from the full, hierarchical reference memory for each combination of ego position and target locations, as illustrated in figure 4.2. Note that in *focal representations* places in the current region become connected to other regions, representing transitions from the current region to adjacent regions. Such transitions are not consistent with common definitions of hierarchical representations of space, in which elements of a region are interconnected to one another and to their super-ordinate region, but not to other super-ordinate regions. However, the transitions do not necessarily have to be represented in long-term spatial memory, but could be created when the *focal representation* is generated in working memory. Transitions from places within the current region to adjacent region entities are crucial for the *fine-to-coarse* planning hypothesis, as explained below.

Figure 4.3, figure 4.4 and the flow chart in figure 4.5 demonstrate the *fine-to-coarse* planning heuristic in detail for one of the test routes of experiment 1 (see type A routes in figure 3.3) and one of the test routes of experiment 2 (see type B routes in figure 3.9). The first step is to generate a *focal representation* from reference memory, current ego position and from the target(s) of the navigation task. The shortest path towards the closest target place or target region, respectively, is planned in the *focal representation*. Here a cost function has to be introduced describing the relative costs of traveling within or between regions. According to how regions are represented in hierarchical spatial memory, e.g., by centroids (Leiser & Zilbershatz, 1989) or by anchor points (e.g., Couclelis, Golledge, Gale, & Tobler, 1987), this cost function will vary. The transitions between different hierarchical levels allow a hypothetical planning mechanism that spreads activation through the *focal representation*, to implicitly switch from fine-space information (place-connectivity) to coarse-space information (region-connectivity), as the distance from the current position increases. Any route plan derived from *focal representations* therefore has detailed instructions for the current surrounding, allowing to make immediate movement decision. The algorithm will execute a single step of the route plan. If a target place was reached, the target list is updated, i.e. the target is removed from the target list. If the target list is empty, the navigation task is completed. Otherwise the algorithm will jump back, update the focal representation and re-plan in order to obtain the next step of the navigation task.

The *fine-to-coarse* planning heuristic is a cognitive model that describes a possible use of the hierarchical structure in spatial memory for human route planning.

The core of the *fine-to-coarse* planning hypothesis is the *focal representation* that represents spatial information at different levels of detail for close and distant locations. A major advantage of *fine-to-coarse* route planning is that any route plan generated in a *focal representation* allows to make immediate movement decisions. If only the next step is taken into account, as suggested above, an agent does not need to remember a planned path, but simply executes a single step of the route plan and only upon encountering the next choice point a new route plan is generated. By this means the route is generated during navigation.

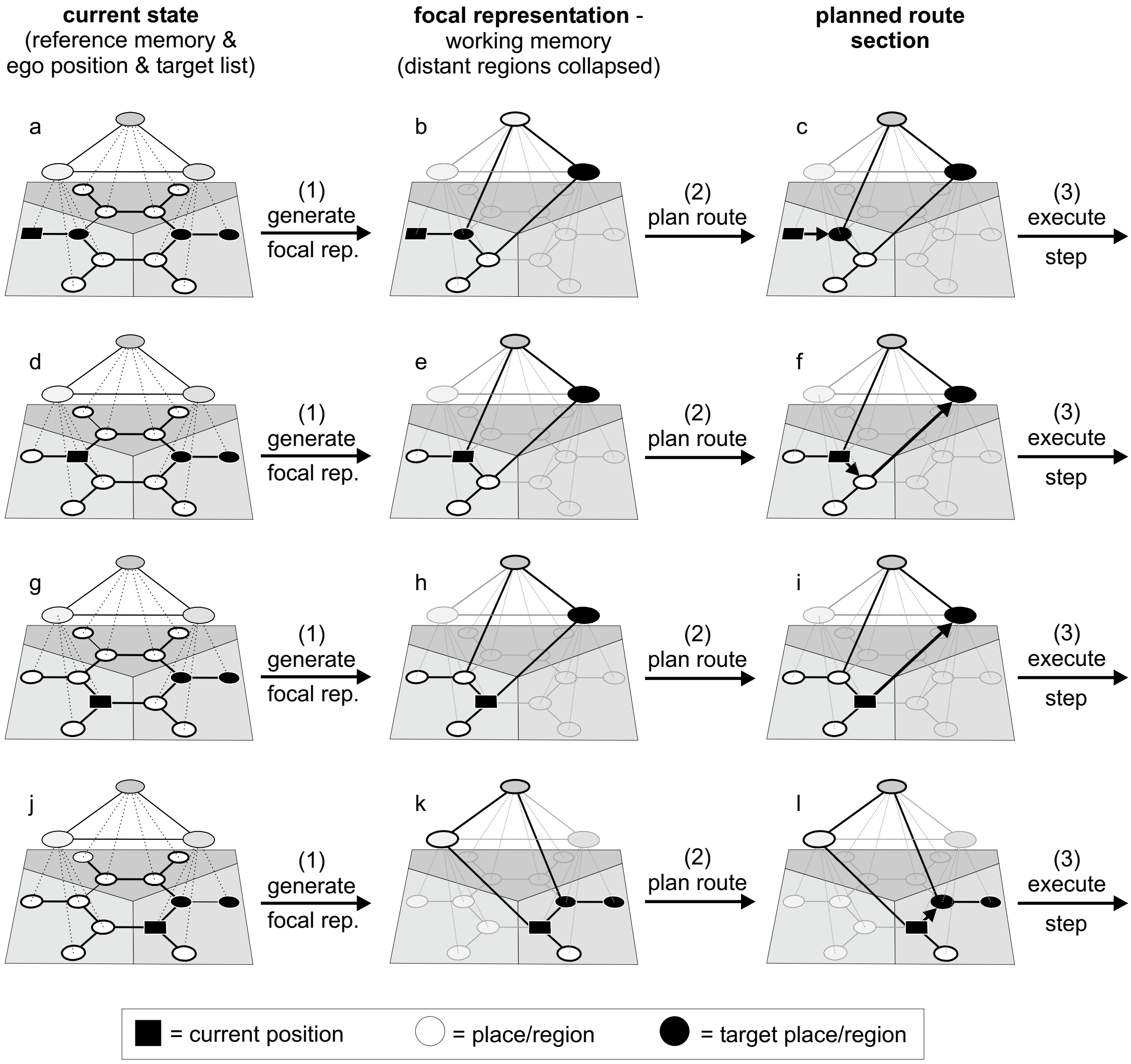


Figure 4.3: *Fine-to-coarse* route planning. left column: current state of the navigation task, superimposed on the spatial reference memory; middle column: focal representation, i.e. working memory used for planning (spatial information at different levels-of-detail is used simultaneously); right column: route section from ego position to next target or region boundary. The routes are displayed by arrows connecting places or region nodes. Operation (1) Generating focal representation from reference memory and targets and ego position as described in figure 4.2. Operation (2) route planning. Operation (3) traveling a route section and restart of planning cycle.

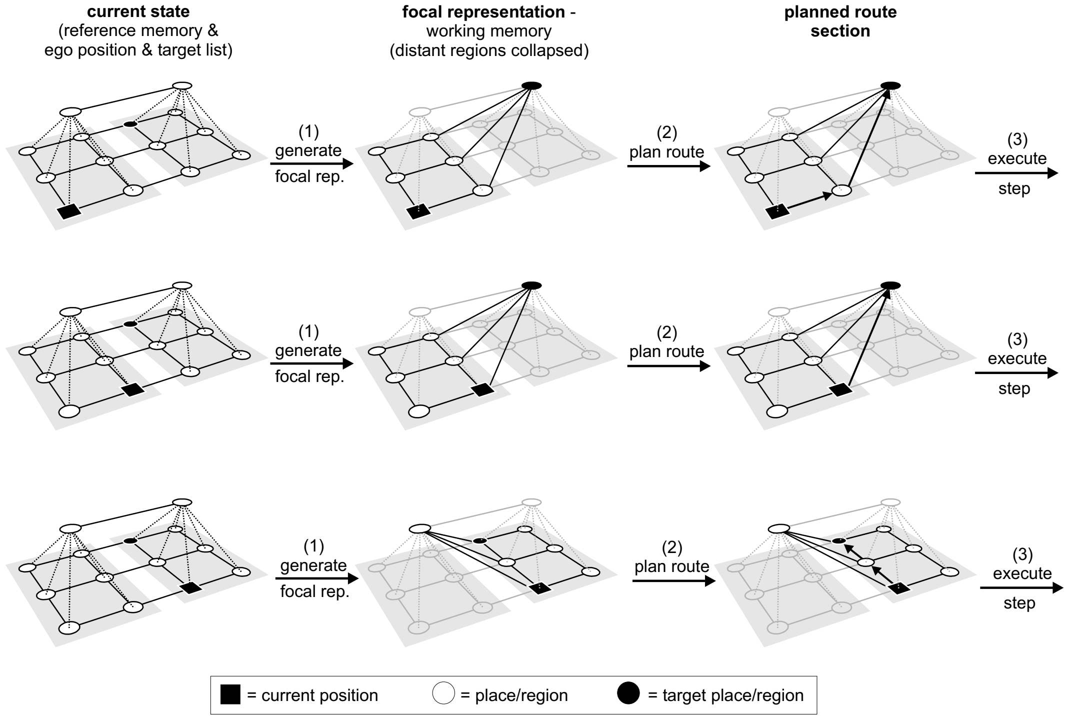


Figure 4.4: *Fine-to-coarse* route planning for type B routes of experiment 2. Left column: current state of the navigation task, superimposed on the spatial reference memory; middle column: focal representation, i.e. working memory used for planning (spatial information at different levels-of-detail is used simultaneously); right column: route section from ego position to next target or region boundary. The planned route is shown by arrows connecting places or region nodes. Operation (1) Generating focal representation from reference memory and targets and ego position as described in figure 4.2. Operation (2) route planning. Operation (3) traveling a route section and restart of planning cycle upon reaching a goal or region boundary.

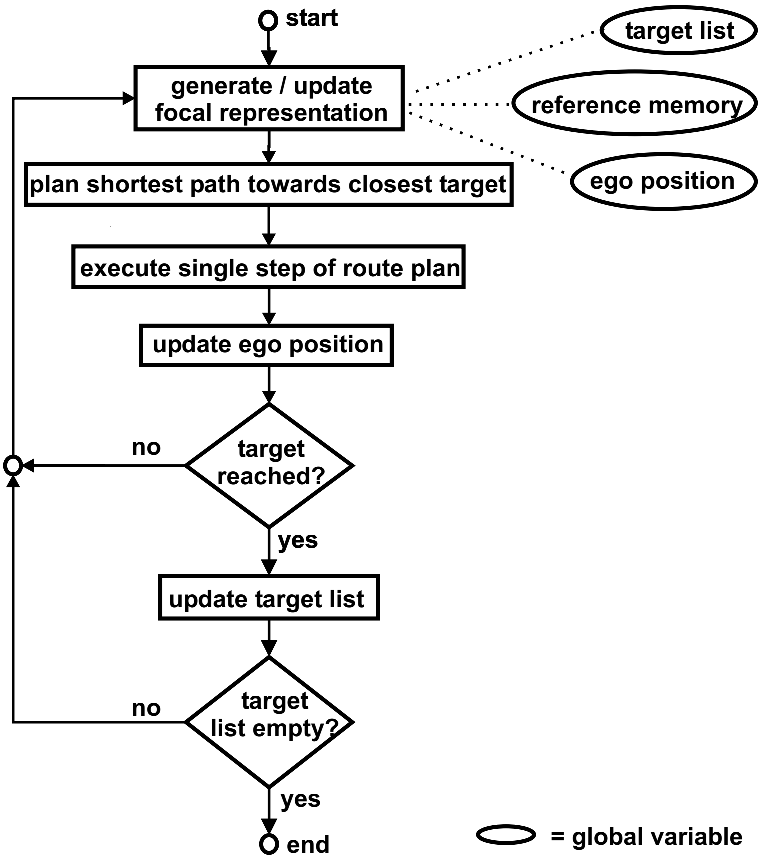


Figure 4.5: A generic flow chart of the *fine-to-coarse* planning heuristic.

Chapter 5

Interaction of Navigation Strategies in Regionalized Environments

In chapter 3 two navigation experiments were presented that investigated the role of environmental regions on human route planning and navigation behavior. In chapter 4 the *fine-to-coarse* planning heuristic was introduced, a cognitive model that describes a possible use of the hierarchical structure of spatial memory for navigation and route planning and that could account for the empirical data. However, route planning can not be described by the means of a single navigation strategy or route planning mechanism. Rather, one has to assume that multiple route planning strategies are present that work together and interact (see Golledge, 1995).

In this chapter, two navigation experiments are reported that were designed to study the use and interaction of three different navigation- and route planning strategies that are applied after learning a regionalized environment when solving navigation tasks with multiple targets. One of the strategies is referred to as *cluster-strategy* and states that the distribution of multiple targets within an environment systematically influences route planning and navigation behavior. The second strategy is called *least-decision-load* strategy and predicts that the complexity of alternative paths is taken into account during route planing. The third strategy is the *fine-to-coarse* planning heuristic (see chapter 4), stating that route planning is based on region-connectivity and not place-connectivity alone.

5.1 Experiment 3

5.1.1 Purpose

This experiment particularly concentrated on the use and interaction of two navigation strategies: (i.) Gallistel & Cramer (1996) have shown that vervet monkeys, when having the choice to first visit a rich or a poor food patch, always go for the rich food patch first (see chapter 1). Here it is studied whether such a navigation strategy, which is referred to as the *cluster*-strategy, is also employed by human navigators when faced with a similar task; (ii.) In experiment 1 and experiment 2 it was demonstrated that environmental regions do influence human route planning behavior. The *fine-to-coarse* planning heuristic, a cognitive model of region-based route planning, was proposed to account for the empirical data (see chapter 4). Essentially the *fine-to-coarse* heuristic states that during route planning, fine spatial information (for example, places) is used for nearby locations only, while coarse spatial information (for example, regions) is used for distant locations and distant places.
The predictions of the *cluster*-strategy and the *fine-to-coarse* planning heuristic for the navigation-tasks in this experiment are explained below.

5.1.2 Methods

5.1.2.1 The Virtual Environments

The virtual environment consisted of 4 islands containing 4 places each. The places were interconnected by roads and bridges and could be identified by associated, unique landmarks (see figure 5.1). The landmarks of the four islands were of four distinct categories. While the landmarks of one island were of the category cars, the landmarks of the other islands were of the categories flowers, animals and buildings. The clustering of landmarks belonging to the same category, as well as the existence of four separated island, ought to facilitate subjects' learning of the environment and ought to establish environmental regions within subjects' spatial memory. Landmarks were only visible when subjects were in close proximity, i.e. at the corresponding place, and are therefore referred to as pop-up landmarks. Subjects' movements were restricted to roads and bridges.

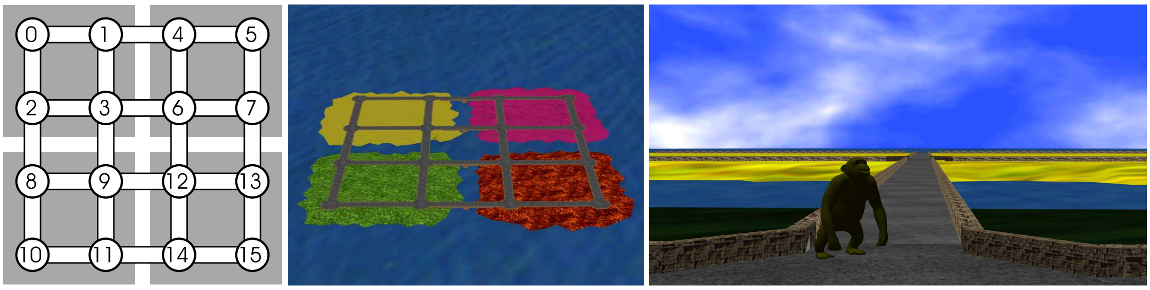
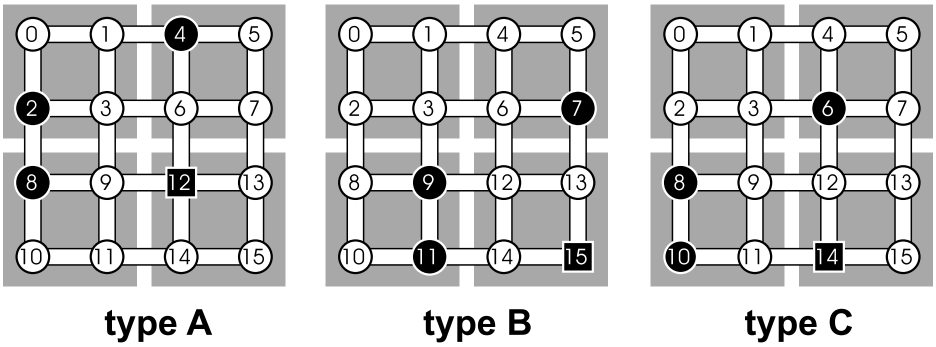


Figure 5.1: left: Schematic map of the virtual environment. Places are displayed as numbered circles, streets and bridges are represented by lines, the gray rectangles represent the islands or regions, respectively; middle: bird's eye view of the environment; right: subjects' perspective with a pop-up-landmark

5.1.2.2 Procedure

After the exploration- and training-phase (see section 2.2) subjects entered the test-phase. During the test-phase subjects were repeatedly asked to navigate the shortest possible route connecting their current position with three places in the environment. According to the spatial configuration of the starting place and the three target places, the navigation tasks were classified as belonging to either the test-routes (see figure 5.2 and table 5.1) or to the distractor-routes (see figure 5.3 and table 5.1). While two of the three target places of the test-routes were neighboring each other, thus forming a spatial cluster, the remaining target place was sole. The test-routes could additionally be assigned to one of three subtypes, depending on the position of the starting place. Test-routes of type A always started from one of the four inner-places (start place was 3, 6, 9 or 12; see figure 5.1), test-routes of type B always started from one of the outer-places (start place was 0, 5, 10 or 15; see figure 5.1) and test-routes of type C started from one of the intermediate places (start place was 1, 2, 4, 7, 8, 11, 13 or 14; see figure 5.1). Note that the spatial configuration of starting- and target-places was identical for routes of type A, B and C. By rotating and mirroring the configuration of starting- and target-places eight different test-routes for each route type were generated. All test routes allowed for alternative solutions of equal length. A detailed description of all test routes can be found in table 5.1.

The distractor-routes were introduced to impede subjects' learning of the spatial configuration of start- and target-places of the test-routes. Distractor routes had a single optimal solution only, not allowing for alternative solutions of equal



type A **type B** **type C**

Figure 5.2: Type A, type B and type C test routes: the black square represents the starting place, the black circles represent the target places; Type A routes always started from one of the four inner-places (start place was 3, 6, 9 or 12), type B routes always started from one of the outer-places (start place was 0, 5, 10 or 15) and type C routes started from one of the intermediate places (start place was 1, 2, 4, 7, 8, 11, 13 or 14).

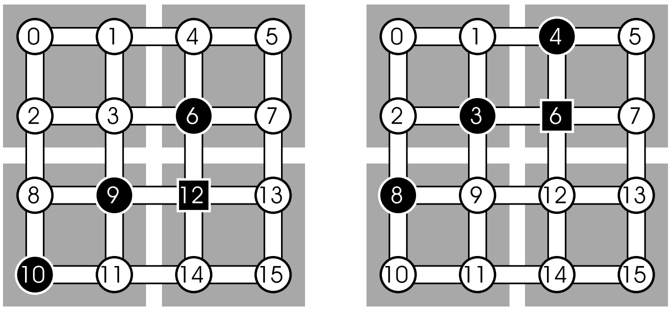


Figure 5.3: Distractor routes, displayed are two examples of the distractor routes.

length. Again, by rotating and mirroring the configuration of start- and target-places a total of sixteen different distractor-routes were generated. A detailed description of all distractor routes can be found in table 5.1.

Subjects were assigned to one of two experimental groups. While subjects of experimental group 1 navigated type A and type B test-routes, subjects of experimental group 2 navigated type A and type C test-routes. In addition both groups also navigated all 16 distractor-routes. In each of two experimental blocks subjects navigated four test-routes of type A, four test routes of type B (experimental group 1) or four routes of type A and four routes of type C (experimental group 2), respectively, and eight distractor routes.

Route Type	Start Place (Target Places)
A	12 (4,2,8), 9 (1,4,13), 12 (4,1,8), 6 (2,8,14), 9 (13,7,1), 3 (11,14,7), 6 (14,11,2), 3 (13,7,11)
B	15 (7,9,11), 10 (14,2,3), 15 (11,6,7), 5 (13,1,3), 10 (2,12,14), 0 (4,8,9), 5 (12,13,1), 0 (4,6,8)
C	14 (6,8,10), 8 (12,0,1), 13 (9,4,5), 4 (12,0,2), 11 (3,13,15), 2 (6,11,10), 7 (14,15,3), 1 (5,7,9)
Distractor-Routes	9 (3,12,15), 3 (6,9,10), 12 (6,9,10), 6 (3,12,15), 9 (12,3,0), 3 (9,6,5), 12 (9,6,5), 6 (12,3,0), 3 (1,6,13), 6 (7,12,11), 12 (14,9,2), 9 (11,12,7), 3 (2,9,14), 6 (4,3,8), 12 (13,6,1), 9 (8,3,4)

Table 5.1: The table lists all test-routes and all distractor-routes. The starting place is followed by the three target places (in brackets). The numbers correspond to the place numbers in the schematized drawings of the environment (see figure 5.1).

After subjects completed a test-route they were teleported to the start-place of the subsequent test-route. For each test route multiple solutions of equal length were possible, whose initial directions differed by 90°. The initial heading of the subjects was in the middle of the route alternatives which therefore appeared at visual angles 45° left and 45° right.

5.1.2.3 Variable of Interest & Predictions

Variable of Interest. As stated above, all test-routes allowed for alternative solutions of equal metric length. One of the main characteristics discriminating these alternative solutions was whether subjects first passed by the clustered target-places or the sole target-place. Subjects' tendency to first pass the spatially clustered targets was evaluated. Since only correct navigations were included in the analysis, chance level with respect to first passing the clustered targets was 50%.

Predictions. The proposed *cluster*-strategy and the *fine-to-coarse* planning heuristic made different predictions for the navigation tasks.

The *'cluster'*-strategy states that subjects preferred to visit as many targets as fast as possible. This strategy predicted that subjects first visited the spatially clustered targets in all types of test routes (type A, type B and type C). On might expect a modulation of the effect size between type A, type B and type C routes. In type A routes the spatially clustered targets are distributed about two islands and might therefore be less apparent as compared to type B and type C routes.

As stated in the introduction (chapter 1), the *fine-to-coarse* planning heuristic proposes that route planning takes place in a *focal representation* that represents both, fine space information (place-connectivity) for current and close locations and coarse space information (region-connectivity) for distant locations. Figure 5.4 demonstrates how such a *focal representation* is generated from hierarchical reference memory for routes of type B and routes of type C. In focal representations places located in distant regions are represented by super-ordinate entities (e.g., regions). The actual route planning algorithm does not distinguish between places and regions, but plans towards the closest target (place or region). For all three route types the clustered and the sole target places were equidistant from the starting place. However, the region containing the clustered targets is closer than the region containing the sole targets for routes of type C only (see figure 5.4). For routes of type A and type B both target regions were equidistant from the starting point. The *fine-to-coarse* heuristic therefore proposed that subjects first passed the clustered targets in routes of type C, while the *fine-to-coarse* heuristic predicted that subjects performed at chance level for routes of type A and for routes of type B.

In contrast to the *fine-to-coarse* planning hypothesis, other hierarchical planning schemes, such as the *coarse-to-fine* planning strategy (see chapter 4 for details), did not predict any systematic effect for type A, type B or type C routes. In *coarse-to-fine* route planning, first a coarse route plan is generated, using a high level of abstraction. This coarse route plan is then broken down and for each step a fine route plan has to be generated. No route plan generated solely at coarse levels of the spatial representation takes into account the agent's position within the starting region. Note also that the representations of routes of type B and type C did not differ at the super-ordinate region-level (see figure 5.4). A *coarse-to-fine* planning scheme would therefore predict no systematic effect with respect to first passing the spatially clustered targets in any of the three test route-types, neither would a *coarse-to-fine* planning scheme predict different navigation behavior for type B routes and type C routes.

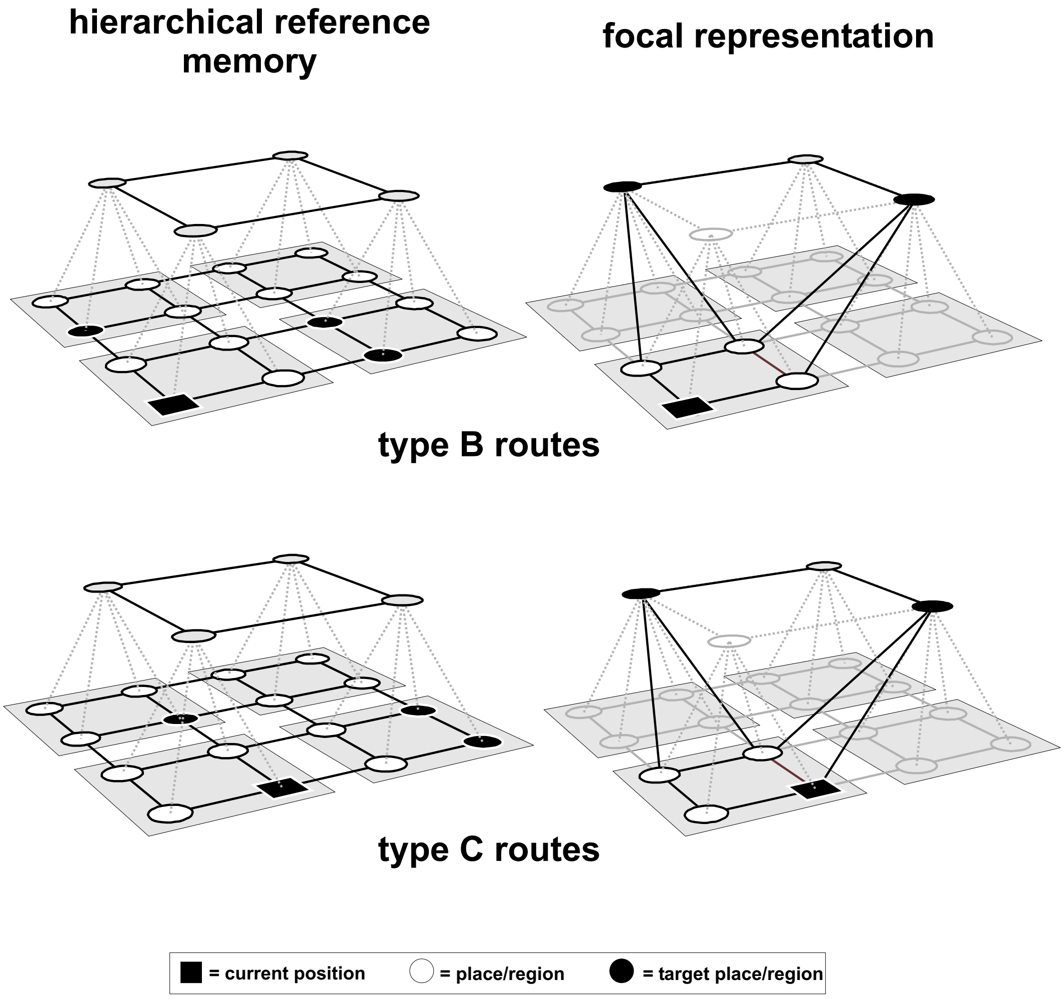


Figure 5.4: Generating a focal representation for routes of type B (upper row) and routes of type C (lower row): Superimposed on the hierarchical reference memory is a navigation task of type B and type C (left column): the black rectangle represents the observer or starting position, respectively, the black circles represent the target places; The black edges and the black circled nodes in the right column represent the *focal representations* existing in working memory in which the route is planned. Only places from the current region are represented at the finest resolution, while distant locations are represented by the region they reside in. Distant target places are also represented by their region. Note that in the *focal representation* of type B routes, both target regions were equidistant from the starting place, while for type C routes the target regions were not equidistant.

5.1.2.4 Participants

Forty subjects were randomly assigned to one of two experimental groups, with 20 subjects per group. Both groups were balanced with respect to gender. Subjects were mostly students of the University of Tübingen, they were paid 8 Euro per hour.

5.1.2.5 Statistical Analysis

See section 3.1.2.5.

5.1.3 Results

Training routes. If a training route was not completed using the shortest possible route, the trial was recorded as an error and the trial was repeated. Subjects' performance during training was measured by counting the repetitions of training trials. On average subjects made 2.2 errors during the training phase. The experimental groups did not differ in their error-rate (experimental group 1: 2.0 errors, experimental group 2: 2.5 errors; Wilcoxon rank sum test: p=.14) and were therefore pooled. Male subjects produced less errors during the 6 training trials than females (male errors: 1.2; female errors: 3.15; Wilcox rank sum test: p=.002).

Subjects' overall Performance. Subjects navigated 74.9% of the navigations in the test-phase error-free, that is to say subjects have found one of the alternative optimal routes. Female and male subjects did not differ in their performance during the test phase (females: 71.8% correct navigations, males: 77.9% correct navigations; Wilcoxon rank sum test: p=.28, see figure 5.5). Subjects' overall performance increased in the second experimental block as compared to the first experimental block (block 1: 68% correct navigations, block 2: 81.8%, Wilcox rank sum test: p=.002, see figure 5.5).

Subjects navigated correctly in 82.0% of the test-routes and in 67.8% of the distractor-routes (Wilcoxon rank sum test: p=.08). Below only error-free test-routes were evaluated.

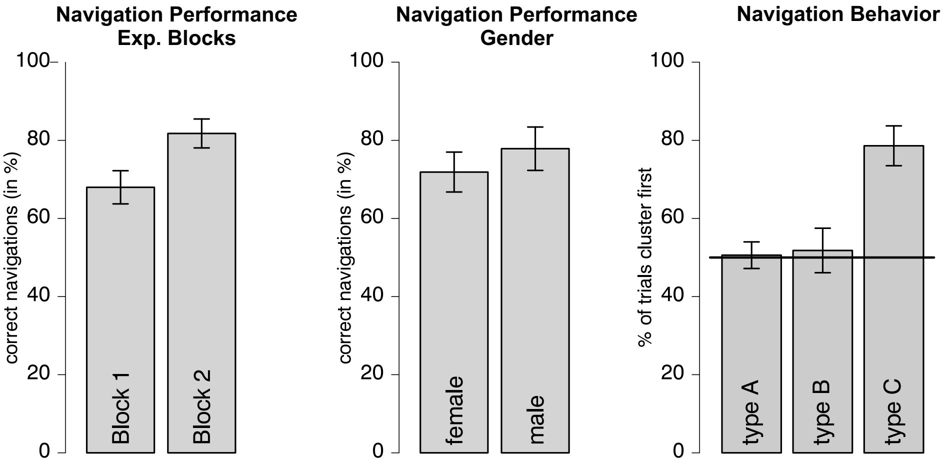


Figure 5.5: left: subjects' performance in experimental block 1 and experimental block 2. Here the percentage of correct navigations are displayed; middle: subjects' performance for male and female subjects; right: subjects' preference to first pass by the spatially clustered targets for the three test routes (type A, type B and type C).

Test Routes (type A, type B & type C routes). Both of the experimental groups navigated test-routes of type A during the test phase. A comparison of subjects' tendency to first pass by the clustered targets in type A routes did not differ between experimental group 1 and experimental group 2 (49.5%, 51.7%, p=.73). Test-routes of type A were therefore pooled across experimental groups.

Subjects performed at chance level with respect to first passing the spatially clustered targets when navigating routes of type A and type B. (type A: 50.6%, Wilcoxon signed rank test against 50%: p=.93; type B: 51.8%, Wilcoxon signed rank test against 50%: p=.67). On the other hand, subjects clearly preferred to first pass the spatially clustered targets when navigating routes of type C (type C: 78.6%, Wilcoxon signed rank test against chance level (50%): p<.001, see figure 5.5).

While a comparison of subjects' navigation behavior between the different route types did not reveal a difference for type A and type B routes (Wilcoxon rank sum test: p=.76), it revealed a significant difference for both, type A and type C comparison and type B and type C comparison (type A routes vs type C routes: Wilcoxon rank sum test: p<.001, type B routes vs type C routes: Wilcoxon rank sum test: p=.001).

Subjects' preference to first pass by the clustered targets when navigating type C routes did not differ between experimental blocks (block 1: 77.9%, block 2: 77.1%; Wilcoxon rank sum test: p=.9), nor between gender (female: 80.1%; male: 77.1%, Wilcoxon rank sum test: p=.70).

5.1.4 Discussion

This experiment was designed to study the influence of environmental regions and the distribution of targets within an environment on human route planning behavior. Although all types of test route had two spatially clustered and a sole target, subjects chose to first visit the clustered targets in only one of the test route types. In both of the other types of test routes subjects' preference to first visit the clustered targets did not differ from chance level. Also subjects' preference was not modulated depending on whether the clustered targets were distributed about two regions or located on the same region. These results suggest that the existence of spatially clustered targets did not influence subjects' route planning behavior in this experiment.

Subjects preferred to first pass the spatially clustered targets in routes of type C only. While in all route types the clustered targets and the sole target were equidistant from the starting place, only in routes of type C the region (the island) containing the clustered targets was closer than the region containing the sole target. This suggests that subjects planned their routes in order to enter the closest target region first, irrespective where exactly the targets were located within that region. These results are in line with the predictions of the *fine-to-coarse* planning heuristic (see section 5.1.2.2). It is important to note that other hierarchical planing schemes as, e.g., the *coarse-to-fine* planning scheme could not account for the observed effect. However, the results provide additional evidence for the notion that human route planning is not based on place-connectivity alone, but takes into account region-connectivity.

An alternative explanation for the observed effect is given when comparing the complexity of alternative optimal solutions for routes of type C. In contrast to the ICD-complexity measure by O'Neill (1991), that measures the complexity of an entire environment in order to compare it to a second environment, here the complexity of alternative routes within the same environment was of interest. A rather crude measure of complexity for routes was used, by simply adding up the possible movement decisions along a path. A lower complexity therefore refers

Strategy	**Place**	**Place**	**Place**	**Place**	**Place**	**Place**	**Place**	**Complexity**
cluster	14 (3)	11 (3)	10 (2)	8 (3)	2 (3)	3 (4)	6	18
cluster	14 (3)	11 (3)	10 (2)	8 (3)	9 (4)	3 (4)	6	19
cluster	14 (3)	11 (3)	10 (2)	8 (3)	9 (4)	12 (4)	6	19
sole	14 (3)	12 (4)	6 (4)	3 (4)	2 (3)	8 (3)	10	21
sole	14 (3)	12 (4)	6 (4)	3 (4)	9 (4)	8 (3)	10	22
sole	14 (3)	12 (4)	6 (4)	12 (4)	9 (4)	8 (3)	10	22

Table 5.2: Comparison of alternative optimal paths to solve type C routes. The first column indicates whether the clustered or the sole targets are visited first. The last column shows the sum of all possible movement decisions. The intermediate columns list the places along the routes, the number of possible movement decisions at the corresponding place are specified in brackets.

to a path that allows for fewer movement decisions. Optimal paths that first passed the clustered targets provided fewer possible movement decisions than paths that first visited the sole target (see table 5.2). That is to say, routes that first passed by the target cluster might have been judged as being less complex than routes that first passed by the sole target. If during route planning subjects took the complexity of alternative routes into account, e.g., in order to reduce the risk of getting lost during navigation, subjects preferred routes along the border of the environment. The strategy to minimize the complexity of a path during route planning is referred to as the *least-decision-load* strategy.

Since in this experiment the navigation tasks did not allow to discriminate between the *fine-to-coarse-* and *least-decision-load* - strategy, one also has to consider that both strategies discussed above (*fine-to-coarse-* and *least-decision-load-*strategy) could account for the observed effect, by, e.g., a linear combination.

5.2 Experiment 4

5.2.1 Purpose

In experiment 3 a systematic effect in subjects' navigation behavior for routes of type C was revealed. Two navigation strategies have been described that could have accounted for the observed effect. This experiment is a modification of experiment 3. By changing the shape of the islands while keeping the absolute positions of the start- and target places of the test routes constant, the influence of the *fine-to-coarse* planning heuristic and the *least-decision-load*-strategy could be studied separately, as well as a possible interaction of these navigation strategies (as explained in detail in section 5.2.2.3).

5.2.2 Methods

5.2.2.1 The Virtual Environment

The virtual environment used in this experiment was similar to the environment used in experiment 3. The only difference was the shape of the islands, which were changed from a squared outline to triangle outlines. The landmarks were moved accordingly, such that still all landmarks of one island were of the same object category. As in experiment 3, the landmarks were only visible when subjects were in close proximity, i.e. at the corresponding place.

5.2.2.2 Procedure

After the exploration- and training-phase (see section 2.2) subjects entered the test-phase. During the test phase subjects navigated exactly the same routes as subjects from the experimental group 2 of experiment 3 (see 5.1.2.2). That is to say, single routes had the same starting place and the same target places in experiment 4 as in experiment 3, irrespective of the shape of the islands (see figures 5.7 and 5.8). Changing the form of the islands resulted in a subdivision of the 2 types of test-routes (type A and type C) from experiment 3 into 4 types of test-routes in this experiment (see figures 5.7 and 5.8 and table 5.3). Again distractor routes

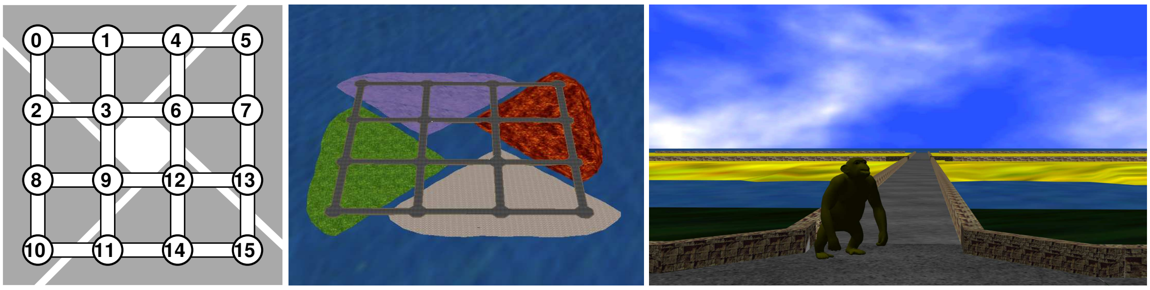


Figure 5.6: left: Schematic map of the virtual environment. Places are displayed as numbered circles, streets and bridges are represented by lines, the gray triangles represent the islands or regions, respectively; middle: bird's eye view of the environment; right: subjects' perspective with a pop-up-landmark

Route Type	Start Place (Target Places)
A 1	12 (4,2,8), 9 (1,4,13), 6 (14,11,2), 3 (13,7,11)
A 2	12 (4,1,8), 9 (13,7,1), 6 (2,8,14), 3 (11,14,7)
C 1	14 (6,8,10), 7 (14,15,3), 1 (5,7,9), 8 (12,0,1)
C 2	13 (9,4,5), 4 (12,0,2), 11 (3,13,15), 2 (6,11,10)
Distractor-Routes	9 (3,12,15), 3 (6,9,10), 12 (6,9,10), 6 (3,12,15), 9 (12,3,0), 3 (9,6,5), 12 (9,6,5), 6 (12,3,0), 3 (1,6,13), 6 (7,12,11), 12 (14,9,2), 9 (11,12,7), 3 (2,9,14), 6 (4,3,8), 12 (13,6,1), 9 (8,3,4)

Table 5.3: The table lists all test-routes and all distractor-routes. The starting place is followed by the three target places (in brackets). The numbers correspond to the place numbers in the schematized drawings of the environment (see figure 5.6).

were introduced to impede subjects' learning of the spatial configuration of start- and target-places of the test routes. The same distractor routes were used that had already been used in experiment 3.

As in experiment 3 subjects navigated 32 routes during the test phase of this experiment; 16 routes were test-routes (4 of each test route type, see table 5.3), 16 routes were distractor routes. In each of two experimental blocks subjects navigated 2 routes of each of the 4 test route types and 8 distractor routes.

After subjects completed a test-route they were teleported to the start-place of the subsequent test-route. For each test route multiple solutions of equal length were possible, whose initial directions differed by 90°. The initial heading of the

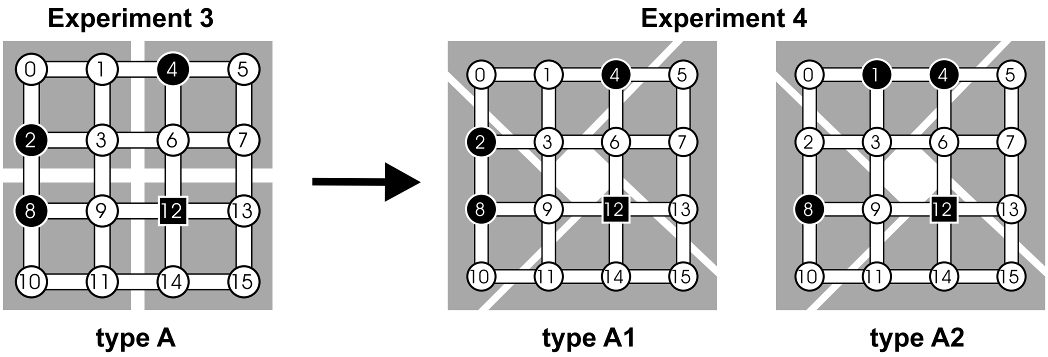


Figure 5.7: The test routes A1 and A2: the black square represents the starting place, the black circles represent the target places. Depicted on the left is route type A of experiment 3. By changing the form of the islands and by mirroring the route along the diagonal centerline, type A1 and type A2 routes were obtained. The *cluster*-strategy and *fine-to-coarse*-planning heuristic made different predictions for type A1 and type A2 routes (see predictions).

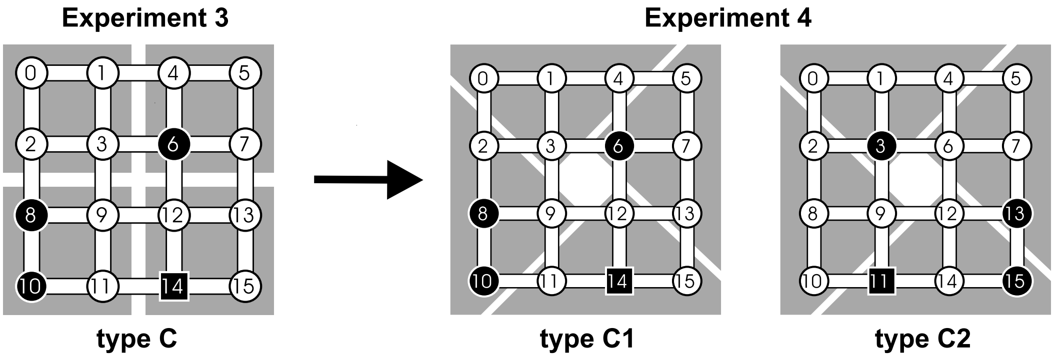


Figure 5.8: test routes: the black square represents the starting place, the black circles represent the target places. Depicted on the left is route type C of experiment 3. By changing the form of the islands and by mirroring the type C routes along the vertical centerline, type C1 and type C2 routes were obtained. The *least-decision-load*-strategy, the cluster-strategy and *fine-to-coarse*-planning heuristic made different predictions for type C1 and type C2 routes (see predictions).

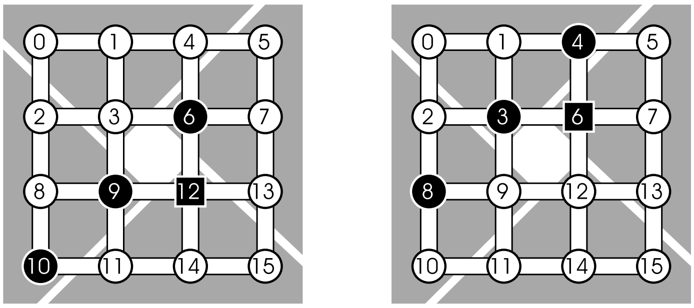


Figure 5.9: The distractor routes; the same sixteen distractor routes as in experiment 3, i.e. the same configuration and the same absolute position of start place and target places, were used. Here two examples of distractor routes are depicted.

subjects was in the middle of the route alternatives which therefore appeared at visual angles 45° left and 45° right.

5.2.2.3 Variable of Interest & Predictions

Variable of Interest. As in experiment 3 all test-routes allowed for alternative solutions of equal metric length. Again subjects' tendency to first pass the spatially clustered targets was evaluated. Since only correct navigations were included in the analysis, chance level with respect to first passing the clustered targets was 50%.

Predictions. Changing the shape of the island in this experiment as compared to experiment 3, while keeping the absolute positions of start- and target-places constant, allowed to study the influence of the *fine-to-coarse*-planning strategy and the *least-decision-load* strategy separately, as well as an interaction of both of these strategies. While for routes of type C in experiment 3 the *fine-to-coarse*-planning strategy and the *least-decision-load*-strategy predicted that subjects first passed by the clustered targets, in this experiment the *fine-to-coarse*-planning- and the *least-decision-load*-strategy made different predictions for routes of type C1, type A1 and type A2, as explained below.

Since both regions containing targets were equidistant from the starting place and in adjacent regions, in routes of **type C1**, the *fine-to-coarse* strategy did not predict any systematic effect; the *least-decision-load*-strategy, on the other hand, predicted that subjects navigate along the border, therefore first passing the clustered targets.

For routes of **type A1** and **type A2**, the *least-decision-load*-strategy did not predict any systematic effect. Paths with the same 'decision-load', i.e. the same number of possible movement decisions, were available, irrespective of whether subjects first passed the clustered or the sole target. However, for type A1 routes the *fine-to-coarse* strategy predicted that subjects first passed by the clustered targets, while for routes of type A2 the *fine-to-coarse* strategy predicted that subjects first passed by the sole target. In type A1 routes the clustered targets, and in type A2 routes the sole target, could be reached by crossing a single region boundary, while two region boundaries had to be crossed in order to reach the other targets (i.e., the sole target for type A1 routes and clustered targets for type A2 routes; see figure 5.7).

For routes of **type C2**, the *least-decision-load*-strategy as well as the *fine-to-coarse*-planning strategy both predicted the same navigation behavior. The *least-decision-load*-strategy predicted that subjects navigate along the border of the environment, therefore first passing the clustered targets. The *fine-to-coarse*-planning strategy predicted that subjects first passed by the clustered targets, because one of the corresponding targets resides in the starting region, while two region boundaries had to be crossed in order to first visit the sole target. If the *least-decision-load*- and the *fine-to-coarse*-planning strategy were linearly combined (as discussed in section 5.1.4) a stronger preference for the clustered target was expected as compared to routes of type C1 in which only the *least-decision-load*-strategy predicted that subjects first pass by the clustered target places.

Obviously, the *cluster*-strategy predicted that subjects first pass by the clustered targets for all route types.

5.2.2.4 Participants

Thirty subjects participated in the experiment. Subjects were balanced with respect to gender. Most subjects were students of the University of Tübingen, they were paid 8 Euro per hour.

5.2.2.5 Statistical Analysis

See section 3.1.2.5.

5.2.3 Results

Training Routes. On average subjects made 1.8 errors during the training phase. Female and male subjects did not differ in their training performance (average male errors: 1.4, average female errors: 2.2; Wilcoxon rank sum test: p=.22).

Subjects' overall Performance. In the test-phase subjects produced 81.3% error-free trials, that is to say subjects found one of the alternative optimal routes. Female and male subjects did not differ in their performance (female: 75.4% correct navigations, male: 87.1% correct navigations; Wilcoxon rank sum test: p=.07). Subjects' overall performance increased in the second experimental block as compared to the first experimental block (block 1: 74.2% correct navigations, block 2: 88.3%, Wilcox rank sum test: p=.004). Subjects navigated 91.8% of the test-routes correctly and 70.6% of the distractor-routes (Wilcoxon rank sum test: p<.001). Below we evaluate the error-free navigations of the 4 types of test-routes only.

Test Routes. Table 5.4 and figure 5.10 summarize subjects' preference to first pass the spatially clustered targets for the different route types. Subjects significantly preferred to first pass the target cluster in routes of type A1, type C1 and type C2, while they performed at chance level (50%) for routes of type A2. A comparison of subjects' preference to first pass the target cluster between type A1 and A2 routes revealed a significant difference (Wilcoxon rank sum test: p=.01), a comparison of type C1 and C2 routes did not reveal a significant difference (Wilcoxon rank sum test: p=.13). Since subjects only navigated two routes of each test route type per block, performance for the experimental blocks was not analyzed separately.

Table 5.4 also summarizes the effects of gender. Only for routes of type C1 a marginally significant differences between female and male subjects was found.

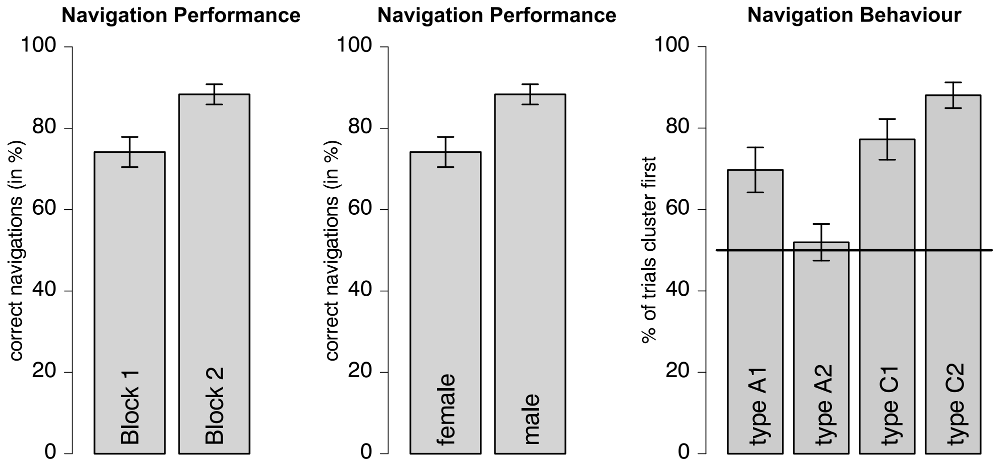


Figure 5.10: left: subjects' performance in experimental block 1 and experimental block 2. Here the percentage of correct navigations are displayed; middle: subjects' performance for female and male subjects; right: subjects' preference to first pass by the spatially clustered targets for the four types of test routes (type A1, type A2, type C1 and type C2).

	cluster first	pValue
Type A1	69.7%	p = .003
Type A2	51.9%	p = .667
Type C1	77.2%	p < .001
Type C2	88.1%	p < .001

	female	male	pValue
Type A1	71.1%	68.3%	p = .57
Type A2	48.8%	55.0%	p = .86
Type C1	86.7%	67.8%	p = .0502
Type C2	93.3%	82.8%	p = .16

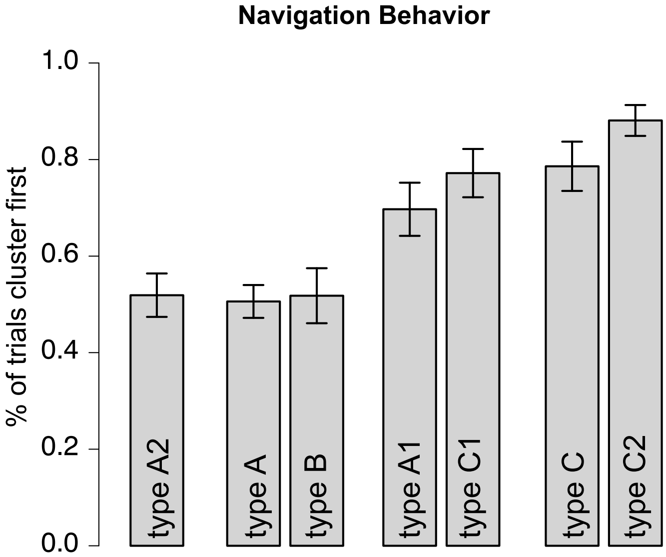
Table 5.4: left: the table summarizes subjects' preference to first pass by the spatially clustered target for the different route types and the p-values for the Wilcoxon signed rank test against chance level (50%); right: the table summarizes female and male navigation behavior separately.

	Cluster	Least-decision-load	Fine-to-coarse	Average strategy pred.	Navigation results
Type A	1	0.5	0.5	0.66	50.60%
Type B	1	0.5	0.5	0.66	51.70%
Type C	1	1	1	1	78.60%
Type A1	1	0.5	1	0.83	69.70%
Type A2	1	0.5	0	0.5	51.90%
Type C1	1	1	0.5	0.83	77.20%
Type C2	1	1	1	1	88.10%

Table 5.5: The table displays the predictions of the proposed 'cluster' - , *least-decision-load*- and *fine-to-coarse* - strategy concerning whether or not subjects first pass by the target cluster (1=yes, 0=no, 0.5=no prediction) for the different route types from experiment 3 and experiment 4. Also the average of the three hypothesis is displayed, as well as subjects' measured preference to first pass the target cluster.

Comparison of results from Experiment 3 & Experiment 4. Experiment 3 and experiment 4 only differed with respect to the shape of the island in the virtual environment. The configuration of start place and target places of the navigation tasks in the test phase was identical between experimental group 2 of experiment 3 (the group that navigated type A and type C routes) and the experimental group of experiment 4. Therefore it was decided to analyze the data from both experiments together by comparing subjects' navigation behavior with the predictions of the three proposed navigation strategies (*cluster*-strategy, *least-decision-load*-strategy and *fine-to-coarse*-strategy).

Table 5.5 summarizes subjects' tendency to first pass the clustered targets for all route types of experiment 3 and 4. Additionally the predictions of the three route planning strategies are listed and whether these planning strategies predict that subjects first pass the clustered targets (1), the sole target (0), or whether they do not predict a systematic preference at all (0.5). In figure 5.11 subjects' preference to first pass by the target cluster is plotted according to the predictions of the three strategies. Assuming the most simple combination of the three navigation strategies (a linear combination with equal weights) the predictions of the three navigation strategies were averaged. Subjects' navigation behavior strongly correlated with the averaged predictions of the three navigation strategies (r=.92, p<.01).



	type A2	type A	type B	type A1	type C1	type C	type C2
cluster	1	1	1	1	1	1	1
ldl	0.5	0.5	0.5	0.5	1	1	1
ftc	0	0.5	0.5	1	0.5	1	1
average	0.5	0.66	0.66	0.83	0.83	1	1

Figure 5.11: The figure displays subjects' tendency to first pass by the clustered targets depending on the predictions of the three proposed navigation strategies (cluster, least-decision-load (ldl) and fine-to-coarse (ftc)). For each navigation strategy and for each route type the predictions are quoted (1=first clustered targets, 0=first sole target, 0.5=no prediction)

5.2.4 Discussion

Subjects showed a significant preference to first pass by the spatially clustered targets in routes of type A1, type C1 and type C2, while they performed at chance level in routes of type A2. A comparison between subjects' navigation behavior and the predictions of the proposed navigation strategies reveals that none of the three navigation strategies alone could account for the empirical data:

Least-decision-load-strategy**:** the *least-decision-load*-strategy predicted that subjects first passed by the spatially clustered targets in routes of type C1 and type C2, while no systematic effect was predicted for routes of type A1 and type A2. The predictions matched the results for type A2, type C1 and type C2 routes, but did not match results for type A1 routes.

Cluster-strategy**:** the *cluster*-strategy predicted that subjects first visited the spatially clustered targets in all route types. These prediction matched the result of type A1, type C1 and type C2 routes, but did not match results of type A2 routes.

Fine-to-coarse planning heuristic**:** The *fine-to-coarse* strategy predicted that subjects first passed the spatially clustered targets in routes of type A1 and routes of type C2, while the *fine-to-coarse* strategy predicted that subjects first passed the sole target in routes of type A2. For routes of type C1 no systematic effect was predicted. The predictions matched results for type A1 and type C2 routes, but did not match results for type A2 and type C1 routes.

Since none of the above navigation strategies alone could account for the results of the current experiment, and since no other navigation strategy was evident that could describe the effects, an interaction between multiple navigation strategies had to be assumed.
This is best demonstrated by an comparison between subjects' behavior when navigating routes of type A1 and A2. The *fine-to-coarse* strategy predicted contradictory outcomes for routes of type A1 and type A2, while the *least-decision-load*-strategy did not predict any systematic effects for these route types. If target clusters did not influence subjects' route planning behavior (as suggested in experiment 3) and if subjects planned their routes in order to enter the closest target region first (as suggested by the *fine-to-coarse* planning heuristic; see experiment 3), they should have first passed by the clustered targets in routes of type A1, while they should have first passed by the sole target in routes of type A2. In fact, results for type A1 routes matched the above predictions, while results for type A2 routes did not. Rather than preferring to first pass by the sole target when navigating routes of type A2, subjects behaved at chance level, choosing to first pass the sole and the clustered targets equally often.

The discrepancies between predictions and results could be accounted for if one assumed that in the current experiment the *fine-to-coarse* planning heuristic, the *cluster*-strategy and the *least-decision-load*-strategy interacted.
Linearly combined, the *cluster*-strategy and the *fine-to-coarse* planning heuristic would add up in routes of type A1, while they would cancel each other out in routes of type A2, exactly predicting the empirical data. The *least-decision-load*-strategy made no prediction for routes of type A1 and type A2.
In routes of type C1 and C2 subjects preferred to first pass by the target cluster. Again, linearly combined, the *cluster*- and *least-decision-load*-effect add up in routes of type C1, both predicting that subjects first passed by the target cluster, while the *fine-to-coarse*-strategy did not predict a systematic effect. In type C2-routes all three navigation strategies (*cluster-*, *least-decision-load-* and *fine-to-coarse*-strategy) predicted that subjects first passed by the target cluster. In fact,

although not statistically reliable, in routes of type C2, in which all three strategies predicted a preference to first pass by the clustered targets, the results revealed a stronger effect than in type C1 routes, in which only two strategies predicted a preference to first pass by the clustered targets. Again, this trend indicates that all three strategies are combined.

It is therefore argued that in experiment 4 the *cluster*-strategy did influence subjects' navigation behavior, while the *cluster*-strategy did not influence subjects' navigation behavior in experiment 3. Such a strategy shift confirms earlier results of Golledge (1995), who has shown that human navigators use different route selection criteria in different environments and on different routes. A possible explanation for the strategy shift between experiment 3 and experiment 4 is given in the following section.

Additional support for the notion that different navigation strategies are used in different environments, comes from a comparison of the results of experiment 2 and experiment 4. In experiment 2 no influence of the complexity of alternative paths on navigation behavior could be found. However, it is argued that the complexity of alternative paths did influence subjects' navigation behavior in experiment 4. The use of different navigation strategies could be explained by the difficulty of the navigation tasks in experiment 2 as compared to experiment 4. In experiment 2 subjects had to find the shortest route from a start place to a single target place within an environment that consisted of 12 places only. In experiment 4, subjects had to find the shortest route for visiting 3 places within an environment that consisted of 16 places. The navigation tasks of experiment 2 were shorter and easier than the navigation tasks in experiment 4. It can be argued that in simple navigation task, in which the risk of getting lost is minimal, the complexity of alternative paths is not taken into account.

5.3 General Discussion of Experiment 3 and Experiment 4

In experiment 3 it was concluded that the *cluster*-strategy did not influence human route planning behavior, and that either of the two remaining navigation strategies (the *least-decision-load-* or the *fine-to-coarse*-strategy) alone, or a combination of the two strategies could account for the empirical data. In experiment

4 neither a single navigation strategy, nor a combination of the *least-decision-load-strategy* and the *fine-to-coarse*-strategy predicted subjects' navigation behavior. It was therefore concluded that in experiment 4 all three navigation strategies (the *cluster*-strategy, the *least-decision-load-* and the *fine-to-coarse*-strategy) interacted.

These results suggest that, by changing the shape of the islands in the experimental environments, a strategy shift occurred between experiment 3 and experiment 4. From the empirical data it is not clear why such a strategy shift would have occurred. A possible explanation is given by Werner & Long (2003) who have shown that the misalignment of local reference systems does result in wayfinding problems and difficulties to understand the overall layout of the environmental structure. In their study Werner & Long investigated the structure of the town hall in Göttingen. The layout of the corresponding floor plan reveals that the elevator is rotated about 45° with respect to the gangways in the floor. That is to say, the salient main axes of the elevator are misaligned with the salient axis of the floor. An user might therefore choose a spatial reference system upon exiting the elevator that is not appropriate for the rest of the floor. Werner & Long argued that the misalignment of different parts within an environment makes integration of spatial knowledge very difficult.
In experiment 4 the main axes of the islands were rotated about 45° with respect to the street grid. Although this misalignment of spatial reference systems did not impede subjects' wayfinding performance, understanding the overall structure of the environment was more difficult in experiment 4 than in experiment 3 (informal interviews with subjects after the experiments). These facts could account for the use of different navigation strategies, or a different weighting of the three navigation strategies, respectively, in experiment 4 as compared to experiment 3.

However, if all route types of experiment 3 and experiment 4 are analyzed together with respect to the average prediction of the three navigation strategies, a highly significant correlation was found. That is to say, a simple linear combination of the *cluster-*, the *least-decision-load-* and the *fine-to-coarse*-strategy with equal weights is sufficient to closely predict subjects' navigation behavior in both experiments.

Chapter 6

Experiment 5: Formation of Hierarchies in Spatial Memory[1]

6.1 Purpose

As stated in the introduction, there is convincing evidence that human spatial memory is hierarchically structured. In chapter 3 and in chapter 5 a series of navigation experiments were presented that revealed an influence of the hierarchical organization of spatial memory on human route planning and navigation behavior. In this chapter a navigation experiment is reported that studied the perception and encoding of environmental regions, i.e. the formation of hierarchical components in spatial memory, during the learning of an environment.

The experiment was motivated by the assumption that regional knowledge that arose early during the process of learning an environment, provided additional information about the environment that could be used to facilitate learning and to compensate for missing or imprecise detailed spatial knowledge. For example, the search for specific locations could be restricted to the appropriate regions.

By executing search tasks, subjects either learned a virtual environment that was divided into different regions or a virtual environment that did not contain predefined regions. Subjects' navigation behavior in the regionalized and in the un-

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[1] The experiment reported in this chapter has been conducted by Alexander Schnee as part of his diploma thesis. The diploma thesis was supervised by Prof. H.A. Mallot and the author.

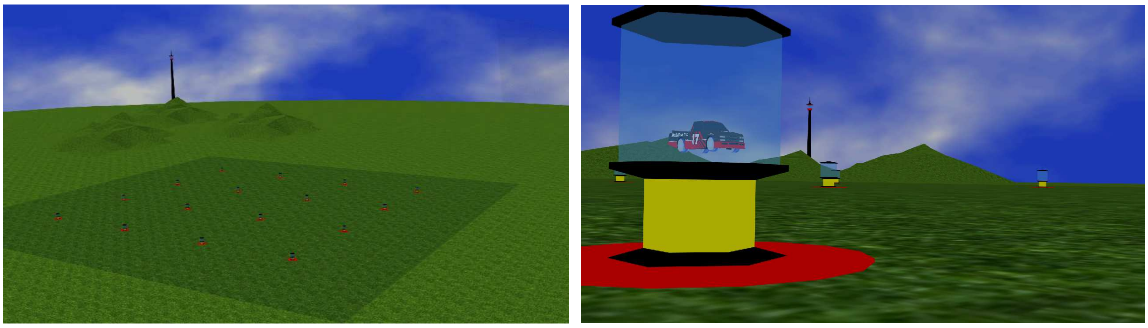

Figure 6.1: a: birds eye view of the virtual environment, the 16 showcases were arranged on a regular grid; b: subjects' perspective with a show case and global landmarks (hills in the background).

regionalized environment was monitored and compared in order to study the perception, encoding and use of regional information.

6.2 Method

6.2.1 The Virtual Environment

An open space virtual environment was created that contained 16 showcases in its center. The showcases were arranged on a 4×4 squared grid with a mesh size of 100m (see figure 6.1). Each showcase was placed on a circular ground plate with a radius of 7.5 m. If subjects moved on the ground plate a single object within the showcase became visible. The objects are therefore referred to as pop-up landmarks, the corresponding ground plates are referred to as the landmarks' catchment areas. While its associated landmark uniquely specified each showcase, the landmarks were grouped into four different semantic groups according to the object category (4 cars, 4 animals, 4 buildings, 4 flowers). Two versions of the virtual environment were created that only differed in the arrangement of the objects within the showcases. While objects from the same object category were neighboring each other in the regionalized environment, the objects were pseudo-randomly distributed about the 16 positions in the unregionalized environment. Figure 6.2 demonstrates the arrangement of the objects within the environment for the two experimental environments.

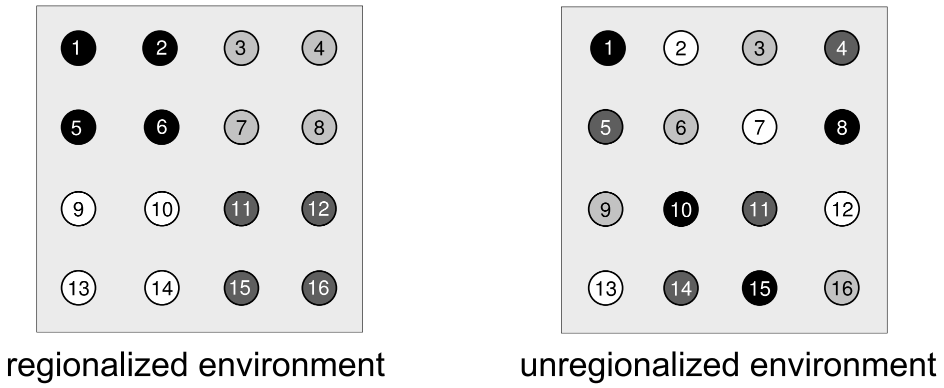

Figure 6.2: left: schematic map of the regionalized environment. The circles represent the positions of the 16 showcases, the 4 different shades of grey represent the 4 different object categories of the landmarks. Landmarks belonging to the same category were neighboring each other, thus forming 4 semantic regions within the regionalized environment; right: schematic layout of the unregionalized environment. The landmarks were pseudo-randomly distributed about the environment.

Four global landmarks were placed in the far distance of the environment to make sure that subjects could always localize themselves (see figure 6.1).

By averaging all distances from all places to all other places carrying objects from the same category, a distance measurement was obtained that described the order of the environment. Mean order for the regionalized environment was 113.8m, mean order for the unregionalized environment was 247.5m.

6.2.2 Procedure

Subjects were randomly assigned to one of two experimental conditions. Subjects from the 'regionalized' condition conducted the experiment in the regionalized environment, while subjects from the 'unregionalized' condition conducted the experiment in the unregionalized environment. Subjects were seated on a bicycle trainer and could freely move through the environment by pedaling (translation) and tilting (rotation) the bicycle. They were repeatedly asked to search for showcases containing a specific object. The target object was presented as an image, that was superimposed on the projection screen. By actively navigating through the virtual environment, subjects searched for the showcase containing the target object. The trial ended when subjects entered a non-visible circular area of 3.5 m radius surrounding the showcase that contained the target object. Subjects were instructed to complete the navigation task using the shortest possible path. In each of two experimental blocks, subjects had to visit each of the 16 objects once. Table 6.1 presents the sequences in which subjects had to search for the objects, the numbers correspond to the number of the showcases in the virtual environment and are independent of the experimental condition (see figure 6.2). Three different sequences (s1, s2, s3) were introduced to control for any specific effect elicited by the sequence in which target locations were visited.

trial	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
S1	4	15	2	9	16	7	13	11	5	14	3	12	1	8	10	16
S2	10	1	12	14	3	9	7	16	6	13	11	4	5	15	2	13
S3	6	4	14	1	7	9	16	3	10	8	2	11	14	13	5	15
trial	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
S1	9	7	14	5	4	11	2	8	15	6	13	12	1	10	3	16
S2	11	1	8	10	3	16	9	7	14	5	15	4	6	12	2	13
S3	8	1	10	16	7	14	5	11	4	6	13	12	3	9	2	15

Table 6.1: Table of the three search sequences (s1, s2 and s3). The numbers refer to the positions of showcases in figure 6.2.

6.2.3 Variable of Interest & Predictions

Variable of Interest. Subjects' trajectories were recorded during the navigation tasks. For each navigation task also the shortest possible path between starting place and target place was computed. By dividing the length of the traveled trajectory through the length of the shortest possible path and subtracting 1 an overshoot value was obtained. By multiplying the resulting value with 100 the overshoot in percent was obtained. An overshoot of 100% therefore corresponded to a path that had twice the length of the shortest possible path. The overshoot values were analyzed as a function of the trials, thus representing subjects' learning of the virtual environment. The main interest concerned the comparison of overshoot values between the two experimental groups. From the recorded trajectories also the number and identity of places visited by the subjects was reconstructed for each navigation task.

Predictions. If regions within an environment were perceived early during the process of learning that environment, it was expected that subjects from the regionalized condition encoded the regional information as soon as possible. That is, because (i.) regional knowledge structures the environment, thus the learning of that environment should be facilitated, and (ii.) regional knowledge allows to apply search strategies that could compensate for imprecise fine spatial knowledge. For example, the search for a specific landmark could be restricted to the region containing landmarks of the same objects category. Taken together, it was expected that subjects from the regionalized condition, once they had perceived and encoded the regions, showed better searching and faster learning performance than subjects from the unregionalized condition.

6.2.4 Participants

44 subjects were randomly assigned to one of two experimental groups, with 22 subjects in each group. The groups were balanced with respect to gender. Subjects were mostly students from the University of Tübingen and were paid 8 Euro an hour.

6.2.5 Statistical Analysis

Data were analyzed using the open source statistics software 'R' (www.r-project.org) and the unix program ANOVA. The error-bars of all data plots in this experiment display standard errors of the mean (s.e.m.).

6.3 Results

Overshoot. Figure 6.3 represents subjects' overshoot performance for both of the experimental groups as a function of the trials. By pooling over all 32 search trials a single overshoot value for each of the two experimental groups was obtained. The average overshoot for the regionalized group was 72.0%, the overshoot for the unregionalized group was 142.3%. The average overshoot of block 1 (trial 1-16) was 108.4% for the regionalized group and 207.7% for the unregionalized group. In block 2 (trial 17-32) the average overshoot was 37.7% for the

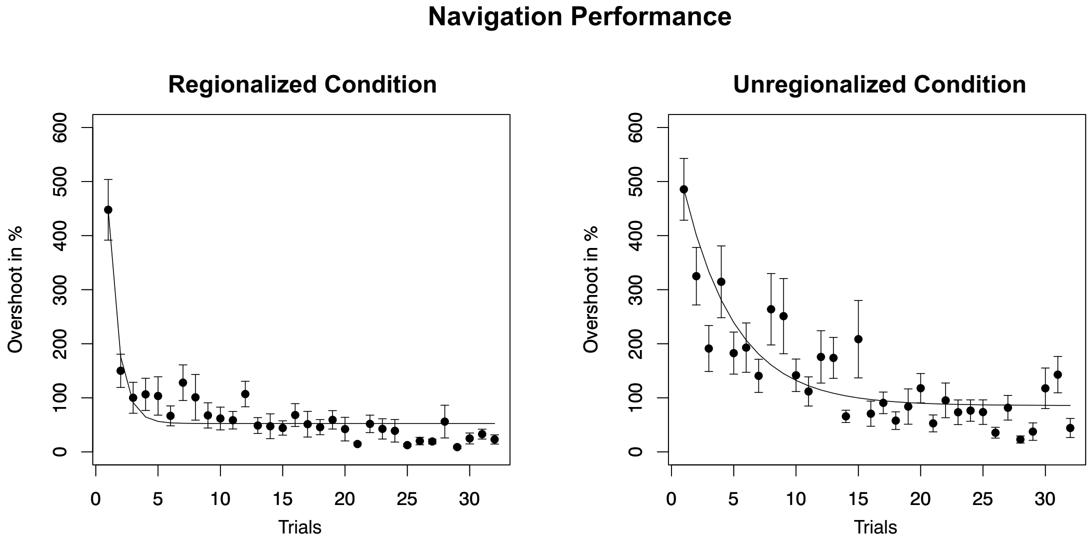

Figure 6.3: Subjects' overshoot values as a function of the trials. The solid lines display the exponential fits. Left: group regionalized; right: group unregionalized.

regionalized group and 76.9% for the unregionalized group.
An analysis of variance (ANOVA) revealed a significant main effect of the experimental conditions (regionalized and unregionalized [F(1, 40)=18.9, p<.001]), a significant main effect of the experimental blocks [F(1, 40)=166.9, p<.001] and a significant groups x blocks interaction [F(1, 40)=13.6, p=.001]. No effect of gender could be found (male overshoot: 94.3%, female overshoot: 120.0%) [F(1, 40)=2.5, p=.12], nor an effect of the different sequences [F(2, 41)=1.2, p=.40].

While subjects from both experimental groups showed comparable navigation performance in the first trial of the experiment (overshoot regionalized: 450.5%, overshoot unregionalized: 487.4%, t-test: t = -.392, df = 41.988, p-value = .697), already in the second experimental trial, subjects from the regionalized condition showed better navigation performance than subjects from the unregionalized condition (overshoot regionalized: 151.7%, overshoot unregionalized: 326.7%,t-test: t = -2.3647, df = 33.58, p-value = .02).

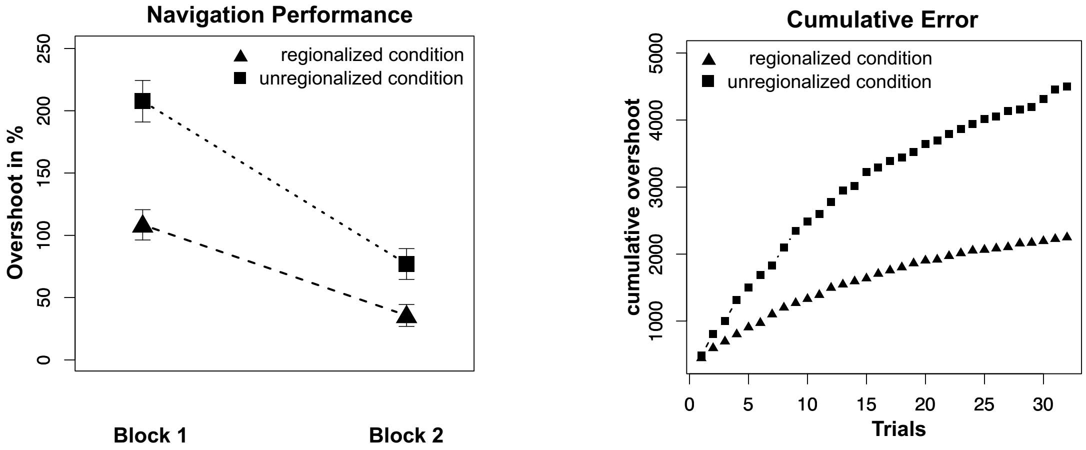

Figure 6.4: left: Subjects' overshoot values for the experimental groups and the experimental blocks; right: the cumulative overshoot for both of the experimental groups.

In order to further quantify the difference between the experimental groups, subjects′ learning behavior was described by an exponential function of the form:

$$l(t) = l_0 + (l_1 - l_0) * e^{-\frac{t-1}{\tau}} \tag{6.1}$$

with:
$t =$ trials
$l_1 =$ overshoot measured at trial 1
$l_0 =$ residual overshoot after prolonged learning (after 32 trials)
$\tau =$ learning rate;

By fitting l_0 and τ separately for both data sets, τ-values of 0.86 (regionalized) and 4.18 (unregionalized) and l_0-values of 52.5 (regionalized) and 85.7 (unregionalized) were obtained. The corresponding fits are displayed in figure 6.3.

The difference of l_1 and l_0 was defined as the learning range during the experiment. From the learning rate τ, the time $t_{0.5}$ can be calculated after which half of the overshoot reduction is achieved:

$t_{0.5} = 1 + \tau * \ln 2$

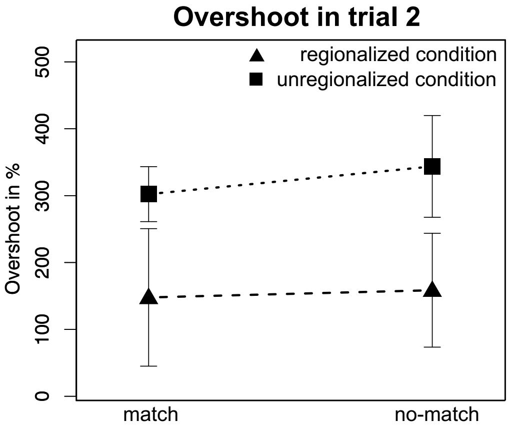

Figure 6.5: Overshoot in the second trial for the regionalized and the unregionalized group depending on whether or not subjects have visited the target of the second trial during their search in the first trial.

Calculating the time $t_{0.5}$ required for half of the overshoot reduction for both of the experimental groups, allowed to compare learning performance, independent of the initial overshoot (l_1) and the residual overshoot (l_0). For the regionalized group $t_{0.5}$ was 1.6, for the unregionalized group $t_{0.5}$ was 3.9. That is to say, subjects from the regionalized condition required only 1.6 trials for half of the overshoot reduction, while subjects from the unregionalized group required 3.9 trials.

Showcases visited. During the first trial of the experiment, subjects from the regionalized condition have visited 9.9 different showcases, while subjects from the unregionalized condition have visited 10.3 different showcases. That is, on average subjects from both of the experimental conditions have seen comparable proportions of all showcases within the environment in the first trial of the experiment (regionalized condition 61.9%, unregionalized condition 64.4%).

Subjects from the regionalized condition showed significant lower overshoot-data in the second trial as compared to subjects from the unregionalized condition. A possible explanation for this effect is, that subjects from the regionalized condition had an improved memory for the exact positions of showcases they had visited in the first trial. If the target of the second trial has already been visited in the first trial, subjects from the regionalized condition would then show better navigation performance.
The second trials of all subjects were therefore split in two groups, depending on whether or not the target of the second trial had already been visited in the

first trial. The 'match group' contained all second trials of which the target had already been visited in the first trial. The 'no-match group' contained all second trials of which the target had not been visited in the first trial. Figure 6.5 displays subjects' overshoot data for both of the experimental conditions and for the 'match group' and the 'no-match group'.

Neither subjects from the regionalized nor from the unregionalized group benefited from visiting the second trial's target place in the first trial (see figure 6.5). Subjects from the regionalized group showed an overshoot performance of 147.8% in the 'match' trials and 158.6% in 'no-match' trials (Wilcoxon rank sum test: p=.62). Subjects from the unregionalized group showed an overshoot performance of 302.2% in the 'match' trials and 343.7% in 'no-match' trials (Wilcoxon rank sum test: p=.85)

6.4 Discussion

The results of this experiment have shown faster learning- and better searching performance for subjects who had learned a virtual environment that was divided into different regions as compared to subjects who had learned a very similar virtual environment that did not contain regions. While in the first trial subjects from both of these experimental groups have shown comparable searching performance, already in the second trial, subjects from the regionalized condition showed better performance than subjects from the unregionalized condition. It is important to note that subjects' performance in the second trial did not depend on whether or not they had already visited the second trial's target during the first trial. This demonstrates that the difference in performance between the experimental groups did not result from faster learning of the exact positions of single objects within the regionalized environment. It is rather suggested that already during the first trial, in which subjects from both of the experimental conditions have visited more than 60% of the environment, the regionalized group has perceived and encoded the regions within the environment. Such regional knowledge structures the space and could therefore facilitate the learning of the environment. Moreover, the existence of regional knowledge allows to apply navigation- and search strategies in order to overcome missing or imprecise information about the environment. For example, in this experiment regional knowledge allowed to assign a target location to a region by simply analyzing the target's object category, even if that target had not been visited before. In order to find the target, subjects now could limit their search space to the appropriate region.

In chapter 3 and chapter 5 four navigation experiments were presented that revealed an influence of environmental regions on human route planning behavior. In chapter 4 a cognitive model of region-based-route planning was introduced, that describes a possible function of the hierarchical organization of spatial knowledge, for route planning. According to this model, regional knowledge allows to reduce both, computational effort and memory load during route planning.

The results of experiment 5 suggest an additional function of hierarchies in spatial memory. Hierarchal organization, here regional knowledge, is used to facilitate learning of an environment, by both structuring space and by providing the basis for search strategies, that could overcome missing or imprecise spatial information.

Chapter 7

Summary and Conclusion

Regions within an environment are known to result in distorted distance-estimations and directional judgments between locations in different regions (e.g., Stevens & Coupe, 1978; Wilton, 1979; Newcombe & Liben, 1982). Also memory recall and recognition times for objects and places within regionalized environments are affected (e.g., Hirtle & Jonides, 1985; McNamara, 1986). These results led to the *hierarchical theories* of spatial representations, stating that spatial memory contains nested levels of detail (for details see chapter 1). Places may be grouped together and form regions, that are represented as super-ordinate entities in graph-like representations of space. The *hierarchical theories* of spatial memory were first introduced in the late 70's. Although numerous studies provided additional evidence for the *hierarchical theories* since, it is still an open question whether such an organization of spatial memory influences human route planning and navigation behavior. The question whether and how route planning is influenced by hierarchical memory organization was the starting point for this work.

In this work route planning referred to the process of selecting of a path from a given starting location to either a single or to multiple goal locations, that are not visible from the start. Given that route planning is an important process acting on spatial memory, it was expected that the hierarchical organization of spatial memory systematically influenced the path choice behavior of human subjects.

The role of hierarchies in spatial memory for route planning and navigation behavior was investigated by the means of five navigation experiments. In each experiment subjects learned a virtual environment that was divided into different regions. Either by studying the learning performance directly (experiment 5), or by evaluating subject's path choice behavior in subsequent navigation tasks (experiment 1-4), the function of hierarchical components in spatial memory for route planning and navigation was investigated.

In **experiment 1** subjects were asked to find the shortest route connecting three places within a virtual environment that was divided into different regions. For each of the critical navigation tasks, alternative solutions were present that only differed with respect to their region characteristics. Subjects reliably preferred paths that crossed fewer rather than more region boundaries. Three alternative hypothesis were presented that could have accounted for the observed effect. The *Distorted-Representation-Hypothesis* (hypothesis 1) stated that during encoding, i.e. during the learning of the virtual environment, a spatial memory was generated that over-represented region boundaries. Thus, paths that crossed more region boundaries would have been perceived as being longer, as compared to paths crossing less region boundaries. The *Persistence-Hypothesis* (hypothesis 2) stated that subjects tend to stay in their current region as long as possible. Such a region-persistence could result from spatial priming. McNamara (1986) has shown stronger priming between location in the same region, as compared to locations in different regions. The stronger pre-activation of places in the current region could result in a preference for paths that stay in the current region rather than leaving the region. In experiment 1, region-persistence would have led to the results described. The *Hierarchical-Planning Hypothesis* (hypothesis 3) stated that route planning uses spatial information at different levels of detail simultaneously. While the close surrounding is represented at fine spatial resolution (place-connectivity), distant locations are represented at coarse spatial resolution (region-connectivity). Planning a route towards a goal-place that resides in a distant regions, implicitly results in a path that enters the region containing the goal as soon as possible, irrespective of where exactly the goal is located within that region. Such a planning algorithm would also account for the results observed. Note that the *Persistence-Hypothesis* and the *Hierarchical-Planning-Hypothesis* both require that regions are explicitly represented in spatial memory. This requirement is in line with the *hierarchical theories* of spatial representations. Simple distortions of memorized distances between places could have accounted for the *Distorted Representation Hypothesis*.

Experiment 2 was designed to distinguish between the different hypothesis of experiment 1. After learning a virtual environment that was divided into two regions, subjects had to navigate routes connecting two places within the environment. For each navigation task at least two alternative solutions of equal length were present. Routes with start location and goal location in different regions allowed to discriminate between the alternative hypothesis. The *Distorted Representation Hypothesis (*hypothesis 1*)* did not predict any systematic effect for these navigation tasks, since subjects had to cross only one region boundary on all alternative paths. An over-representation of inter-region distances would not result in alternative paths with different perceived length. The *Persistence Hypothesis* (hypothesis 2) stated that subjects stay in the starting region as long as possible, predicting that subjects postponed the crossing of the region boundary as long as possible. The *Hierarchical-Planning Hypothesis* (hypothesis 3) predicted that subjects enter the region containing the target place sooner rather than later, irrespective of where exactly the target place is located within that region. Results from experiment 2 were in line with the *Hierarchical-Planning Hypothesis* only.

From the results of experiment 1 and experiment 2 it was concluded that regions are explicitly represented in human spatial memory. This finding is not surprising, since research on the structure of human spatial memory has suggested that regional knowledge is represented in spatial memory in a hierarchical fashion. However, to the author's knowledge the results described in experiment 1 and experiment 2 for the first time revealed an influence of environmental regions on route planning and navigation behavior. Also, the results allowed to reason about the role of regions for route planning. Based on the *Hierarchical-Planning Hypothesis* a cognitive model of region-based route planning, the **fine-to-coarse planning heuristic**, has been developed in chapter 4. In order to plan a route from memory, the relevant spatial information has to be activated in working memory. The *fine-to-coarse* planning heuristics assumes that in working memory a *focal representation* is generated from hierarchical reference memory. In *focal representations* the current location and the close surrounding are represented at fine resolution, while distant locations are represented using super-ordinate entities of the corresponding hierarchical representation of space. Planning a route using a *focal representation* results in a detailed plan for the close surrounding, that is, a plan that allows for immediate movement decisions. For distant locations only coarse information at the region level are given. The route plan therefore has to be refined during navigation. By updating the focal representation according to the current location and by re-planning the route, a detailed plan for the next movement decisions is available at any given step on the route. By using spatial information at different levels of detail for close and distant locations not only the working memory load is reduced, but also the complexity of the planning task itself. Additionally the memory load for the route plan is minimized, since steps are planned only one at a time.

The *fine-to-coarse* planning heuristics demonstrates a possible function and use of hierarchies in spatial memory for route planning. As other hierarchical planning strategies (for example, coarse-to-fine route planning, see chapter 4) the hierarchical structure is used to reduce the complexity of the planning task.

In everyday navigation and route planning multiple information sources and multiple navigation strategies are available. Experiment 1 and experiment 2 were designed to study the role of regions in spatial memory for human route planning. In both of these experiments it was carefully controlled for the use of other navigation strategies. However, it is a naive assumption that route planning relies on a single strategy, such as the described *fine-to-coarse* planning heuristics, only. Therefore **experiment 3** and **experiment 4** investigated the use and the interaction of multiple navigation strategies. Again subjects were asked to find the shortest possible route connecting three places within environments that were divided into different regions. In addition to the *fine-to-coarse* planning heuristic two other navigation strategies were identified that influenced subjects' navigation behavior, the *cluster*-strategy and the *least-decision-load*-strategy. The *cluster*-strategy was first reported by Cramer & Gallistel (1997), who could show that vervet monkeys, when having the choice to first visit a small or a large food patch, always visited the larger food patch first. Essentially, the *cluster*-strategy predicted that route planning takes into account the distribution of target locations within an environment. The *least-decision-load* strategy states that subjects, when having the choice between alternative path, choose the path that minimizes the number of possible movement decisions. Such a strategy could be employed, because the risk of getting lost is smaller on less complex routes. While none of the three strategies alone could account for the observed navigation behavior, a combination of the strategies closely predicted subjects' navigation behavior.

Experiment 3 and experiment 4 also allowed to discriminate between different hierarchical route planning schemes. Results were consistent with the *fine-to-*

coarse planning heuristics, while the results could not be described by the other hierarchical planning schemes discussed in chapter 4.

While experiments 1-4 studied the use of hierarchical components in spatial memory for route planning, **experiment 5** was designed to study the formation and the use of regional knowledge during the learning of an environment. It was expected that, if the regions in the environment were perceived during learning, these regions were encoded in spatial memory sooner rather than later. Already during the learning process an agent could benefit from regional information, i.e. hierarchical organization of spatial knowledge. First, by creating regions the space is structured, thus the learning of an environment could be facilitated. Second, by employing heuristics, regional knowledge, i.e. coarse spatial information, allows to partly compensate for imprecise fine spatial knowledge. For example, regional knowledge might allow one to limit the search for a specific location or object to the corresponding region. Naive subjects were placed in either a virtual environment that was divided into different regions or an environment that did not contain regions. Subjects were then repeatedly asked to find objects within the environment using the shortest possible route. By monitoring search performance in the regionalized and the non-regionalized environment, the influence of regions on the learning process was investigated. Subjects performing the experiment in the regionalized environment showed better search performance already after the first experimental trial. The findings were interpreted as follows: Subjects from the regionalized group perceived and learned the regions within the environment already after one experimental trial. The knowledge about the regions then allowed subjects to minimize their search space to the corresponding region. These results suggest a functional role of regional knowledge in spatial memory already during the learning of an environment.

Taken together, to the author's knowledge this work for the first time revealed an influence of the hierarchical structure of human spatial memory on route planning and active navigation behavior. It was demonstrated that regions within an environment were represented in spatial memory (as suggested by the hierarchical theories of spatial representations) and that these regions resulted in systematic effects on route choice behavior.

The *fine-to-coarse* planning heuristic, a cognitive model that describes a possible function of hierarchical components in human spatial memory for route planning, was developed. As other hierarchical planning schemes the *fine-to-coarse* planning heuristic uses the hierarchical organization of spatial memory in order to reduce the complexity of route planning tasks. In contrast to other hierarchical route planning schemes, the *fine-to-coarse* planning heuristic also reduces the memory load, by assuming that routes are generated during navigation.

The mentioned reduction of both, the planning complexity and the memory load for planned routes, due to the use of hierarchies during route planning, illustrates a possible explanation for the existence of hierarchies in spatial memory.

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