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# ‘Fine-to-Coarse’ Route Planning and Navigation in Regionalized Environments

Jan M. Wiener
*University of Tübingen*
*Max Planck Institute for Biological Cybernetics*

Hanspeter A. Mallot
*University of Tübingen*

Environments that are divided into regions lead to hierarchical encoding of space. Such memory structures are known to systematically distort estimates of distance and direction and affect spatial priming and memory recall. Here we present two navigation experiments in virtual environments that reveal an influence of environmental regions on human route planning and navigation behaviour. Following the hierarchical theories of spatial representations, it is argued that environmental regions are explicitly represented in spatial memory and that human route planning takes into account region-connectivity and is not based on place-connectivity alone. We also propose a *fine-to-coarse* planning heuristic that could account for the empirical data by planning in a representation that uses fine-space information for close locations and coarse-space information for distant locations simultaneously.

**Keywords:** route planning, hierarchical representations of space, regions, navigation, wayfinding, route selection

## 1 Introduction

Hierarchical theories of spatial representations propose that spatial memory contains nested levels of detail (Stevens & Coupe, 1978; Hirtle & Jonides, 1985;

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Correspondence concerning this article should be addressed to Jan M. Wiener, Cognitve and Computational Psychophysics Department, Max Planck Institute for Biological Cybernetics Spemannstrasse 38, 72076 Tübingen, Germany, email: jan.wiener@tuebingen.mpg.de

McNamara, 1986). 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. Evidence for these hierarchical theories comes from a wide variety of experimental paradigms that reveal systematic distortions in human spatial memory.

Stevens and 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 and Jonides (1985) and McNamara (1986). Hirtle and 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 and Rueter (1980) to the recall protocols, Hirtle and 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, distances between clusters were overestimated in absolute distance estimations.

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.

It has been suggested that hierarchical spatial memory is realized in a graph-like representation. In this work we emphasize 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. This concept is contrasted with map-like 2-dimensional representations of space, as put forward by the literal meaning of the phrase ‘cognitive map’. Evidence for graph-like representations of space comes from navigation experiments in animals and humans.

The desert ant *Cataglyphis fortis,* e.g., 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, and Wehner (1998) have shown that these segments partly consist of stored local vectors, associated with visual landmarks (see also Collett, Collett, & Wehner, 2001; Collett & Collett, 2002). Similar results also come from other insect species, such as the honeybee (Menzel, Geiger, Joerges, Mller, & Chittka, 1998; Wehner, Michel, & Antonsen, 1996). 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., Arbib & Lieblich, 1977; Kuipers, 1978, 2000; Leiser & Zilbershatz, 1989; Chown, Kaplan, & Kortenkamp, 1995). Schlkopf and 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 behaviour necessary to move between the corresponding nodes. The view-graph is a parsimonious representation of space that allows for complex navigation behaviour such as route-planning. In navigation experiments in virtual environments, Gillner and 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 and Mallot (2000). Steck and 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 memory consists of bits and pieces of spatial information that are not integrated into a single 2-dimensional map-like representation of space (see also Tversky, 1993). Although the above evidence describes graphs that lack the hierarchical component, it demonstrates that graph-like representations of space are both, ecologically sensible (i.e., minimalistic) and sufficient.

Evidence for hierarchical representations of space has come from a wide variety of experimental paradigms, including distance- and direction-judgments, recall procedures and reaction times. However, although the ultimate purpose of spatial memory is to support navigation, little is known about the influence of hierarchical memory organization on the mechanisms, strategies and heuristics underlying human route planning. One of the few studies on the role of regions for human route planning 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 segment of routes 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.

Here we will present two navigation experiments that reveal an influence of environmental regions on human route planning and navigation behaviour. We will point out and discuss three hypotheses describing how environmental regions do influence spatial memory, navigation and route planning behaviour. The *Distorted Representation* hypothesis (H1) assumes that environmental regions lead to distorted representations of space, that account for systematic biases in navigation and route planning. The *Persistence* hypothesis (H2) suggests that regions are explicitly represented in spatial memory and that subjects prefer to stay in their current region as long as possible, delaying region transitions. The *Hierarchical Planning* hypothesis (H3) states that humans plan routes using different levels of the hierarchical representation of space. That is to say, human route planning takes into account region-connectivity and is not based on place-connectivity alone. We will argue that only the *Hierarchical Planning* hypothesis (H3) is consistent with results from both of the experiments.

We will then present the *fine-to-coarse* planning heuristic, a specific implementation of the *Hierarchical Planning* hypothesis. In *fine-to-coarse* planning a single route plan is generated that contains fine-space information for the close surrounding and coarse space information for distant locations. This plan is updated during navigation in an iterative manner, such that fine space information for immediate movement decisions is available at all times. It is important to note, that the *fine-to-coarse* planning heuristic is critically different from other planning mechanisms that make use of the hierarchical structure in spatial memory, as e.g., *coarse-to-fine* planning. In *coarse-to-fine* route planning multiple plans with different levels of detail are generated successively. The result is a detailed ("fine") plan which is generated before the navigation starts and which has to be kept in mind until the goal is reached.

## 2 General Methods

Both 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 both experiments we designed a particular virtual environment that was created using the software Multigen Creator (MultiGen-Paradigm). A detailed description of the virtual environments is given in the methods sections of each experiments (see sections 3.2.1 and 4.2.1).

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 that we designed and programmed. 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) with a rate of 36 frames per second and an overall resolution of approximately 3500 × 1000 pixels.

Subjects were seated in front of this screen (see Figure 1) either at a table (Experiment 1) or on a bicycle trainer (Experiment 2). The experimental setup allowed for a 180 deg horizontal and a 50 deg 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, and Blthoff (1998).

### 2.2 Procedure

Both experiments were divided into three different phases: a free exploration-, a training- and a test-phase.

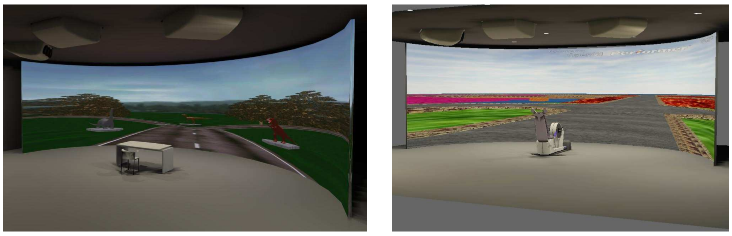

*Figure 1.* The experimental setup.

*Exploration-phase.* During the 10 minute exploration-phase subjects could explore the environment. They 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.* During the training-phase subjects were 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 the navigation task was repeated until they 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 of Experiment 1 and Experiment 2 (see section 3.2.2 and 4.2.2).

## 3 Experiment 1

### 3.1 Purpose

This study was designed to reveal the influence of regions within an environment on human spatial memory and navigation behaviour such as route planning. 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 with multiple destinations. The critical navigation tasks in the test phase provided multiple solutions that led through different numbers of regions.

*Figure 2.* left: 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: birds-eye view on the environment; right: subjects view approaching a place with the corresponding landmark

## 3.2 Methods

### 3.2.1 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 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 2). 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, buildings). A region consisted of two neighboring places within the ring and their associated dead-ends. Pilot studies have shown that spatial clustering of landmarks that belong to the same object category are 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 they could move to the next place by hitting the middle button of the mouse. The movements followed a predefined velocity profile. Rotations ended after a 60 deg turn, translations at the next place.

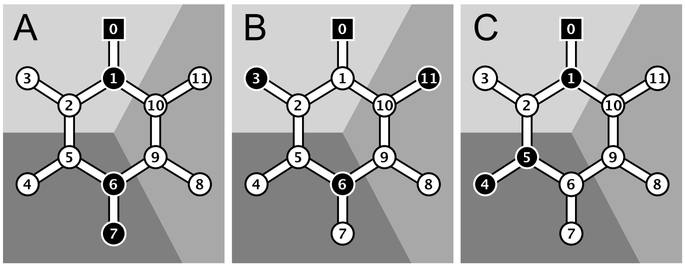

*Figure 3.* The route types (left: type A-, middle: type B-, right: type C- routes). The black squares represent the start places, the black circles represent the goal places. Type A and B navigation tasks (symmetric route types) could be solved on two alternative routes; type A: solution 1: 0,1,2,5,6,7 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).

### 3.2.2 Procedure

After the exploration- and training phase (see section 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), 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 deg around the centre of the environment, we generated six different routes of each type. By this means we generated a total of 18 different test routes and balanced for left/right movement decisions. Subjects navigated all 18 test-routes in each of two blocks. After subjects completed a test-route they were teleported to the start-place of the subsequent test-route, such that subjects were facing the start-place's landmark.

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

### 3.2.3 Variable of Interest

As mentioned above, the experiment was designed to investigate the role of environmental regions on human route planning behaviour. When navigating the symmetric navigation tasks (type A and type B) 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 number of region boundaries that had to be crossed. For each subject 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 we expected subjects to choose between the alternative solutions (less or more boundaries) with the same frequency. Chance level is therefore 50%. In order to reduce noise we only evaluated error free navigations, that is to say when subjects found one of the two alternative short solutions.

## 3.3 Statistical Analysis

Data were analysed 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 multiple trials a normal distribution was not given. We therefore applied the non-parametric Wilcoxon's signed rank test to the data when comparing to a given chance level and Wilcoxon rank sum test for comparison between groups. Using the 'exactRankTests'-package for R we corrected for ties (available from: http://cran.au.r-project.org).

The error bars of all barplots in this study display standard errors of the mean (s.e.m.).

## 3.4 Participants

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

## 3.5 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

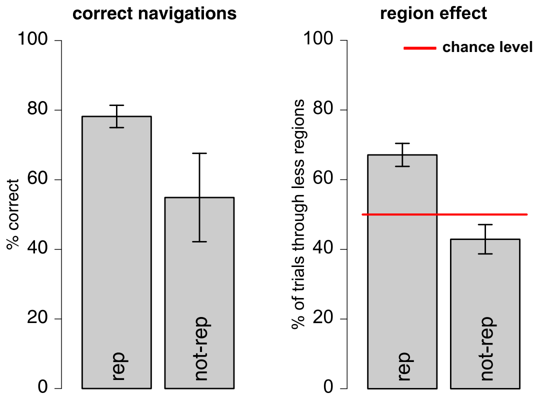

*Figure 4.* left: Subjects overall performance during the test phase for the 'reported' (n = 21) and 'not reported' group (n = 4); right: subjects preference for paths that cross fewer region boundaries when navigating symmetric routes (type A and B) for the 'reported' and 'not reported' group.

errors, while female subjects produced 3.58 errors on average (Wilcox rank sum test: p = 0.27).

*Test routes.* After the experiment subjects were debriefed. 21 out of 25 subjects reported that they had recognized the regions that we introduced in the environment. The remaining four subjects insisted that they had not perceived the car-, animal- and art-region in the environment. We evaluated these two subject groups (group 'reported' & group 'not-reported') 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 54.9 % of the test-navigations (see Figure 4), the difference did not reach statistical significance (Wilcoxon rank sum test: p = 0.09).

Pooling data of type A and type B test-routes, we analysed subjects' overall preference to minimize the number of region boundaries crossed along a symmetric route. A Wilcoxon Rank Sum Test reveals a significant difference between the 'reported' and 'not-reported group' (Wilcoxon rank sum test: p = 0.004; see Figure 4). While the subjects of the 'not-reported'-group performed at chance level (Wilcoxon signed rank test: 42.9% against chance level (50%), p = 0.5), subjects of the 'reported'-group significantly preferred routes that crossed fewer region boundaries (67.1% against chance level (50%), $p < 0.001$). Subjects that have not recognized the regions within the environment did not show a 'region effect', we therefore disregarded these subjects from the rest of the analysis.

A comparison between female and male subjects did not reveal a significant

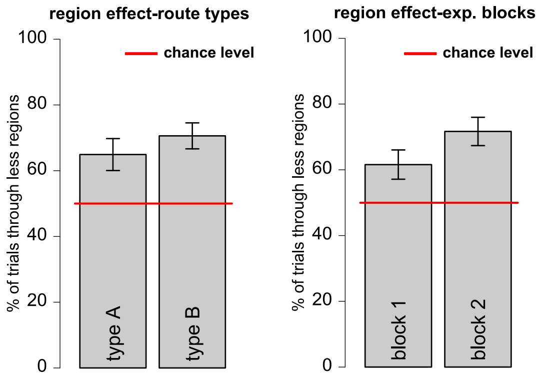

*Figure 5.* left: Subjects preference for routes that cross fewer region boundaries for type A and type B routes (collapsed over experimental blocks); right: subjects preference for routes that cross fewer region boundaries for the experimental blocks (collapsed over type A and B routes).

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 it in 68.3% (Exact Wilcoxon rank sum test: p = 0.69).

The symmetric routes of the test phase could be subdivided into two route types (see Figure 3: type A- and B-routes), that differed mainly in the overall length. Subjects' preference for routes that cross fewer region boundaries did not differ between type A and type B routes (A: 64.9%, B: 70.6%, Wilcoxon rank sum test: p = 0.44, see Figure 5).

In the second experimental block of the test phase, subjects tend to show an increased preference for routes that cross less region boundaries, still this trend does not reach statistical significance (block 1: 61.6%, block 2: 71.7%, Exact Wilcoxon rank sum test: p = 0.12, see Figure 5).

## 3.6 Discussion

Subjects who have recognized the semantic regions within the environment, preferentially navigated routes that crossed fewer rather than more region boundaries. This effect reveals an influence of environmental regions on human route planning behaviour. 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 routes that cross fewer region boundaries do 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 touch on more places in the goal region (that is to say, routes that cross fewer region boundaries). This explanation suggests that the region-effect should be reduced by prolonged learning. If anything, our 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). Our 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 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 we discuss three possible hypotheses (H1 - H3) or planning strategies, respectively, that could account for the observed region effect.

*H1 - Distorted Representation.* Multiple experiments have shown that regions within an environment distort distance estimations (see introduction). 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 cross region boundaries would be over-represented as compared to streets that do not cross a region boundary. Therefore routes that cross fewer region boundaries would appear shorter than routes that cross 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 implicitly result in a preference for routes that cross 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 we will present data that allows to distinguish between the different hypothesis.

# 4 Experiment 2

## 4.1 Purpose

In Experiment 1 we have shown an influence of regions within an environment on human route planning behaviour. Subjects preferred routes that crossed fewer region boundaries rather than alternative routes of equal length. We have discussed three strategies that could account for the observed effect. Experiment 2 is designed to discriminate between these different strategies, since the strategies lead to different predictions in the navigation tasks, as explained below.

## 4.2 Methods

### 4.2.1 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 6) and could be identified by associated, unique landmarks. 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, 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.

### 4.2.2 Procedure

After the exploration- and training-phase subjects entered the test-phase. During the test phase, subjects were asked to navigate the shortest 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

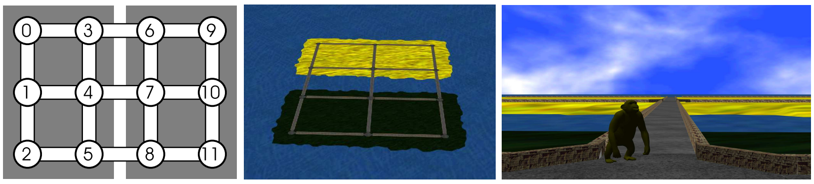

*Figure 6.* left: Schematic map of the experimental environment. Places are displayed as numbered circles, streets and bridges are represented by lines, the gray rectangles represent the islands respectively the regions; middle: bird's eye view of the environment; right: subject's perspective with a pop-up-landmark (ape).

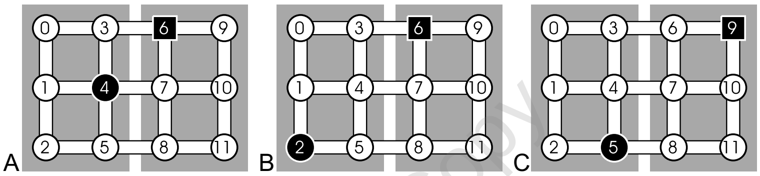

*Figure 7.* The square test-routes. The black square and circle represent start- and target-place, respectively. The square routes can be classified as short routes (type A) and long routes (type B and C). Type B and type C routes differed in the distance of starting and goal place from the region boundary.

was superimposed on the screen. According to the spatial configuration of start- 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 7) or the rectangular test-routes (see Figure 8).

We generated multiple routes of each route type 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 1 for detailed descriptions of the test routes). 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 deg. The initial heading of the subjects was in the middle of the route alternatives which therefore appeared at visual angles 45 deg left and 45 deg right.

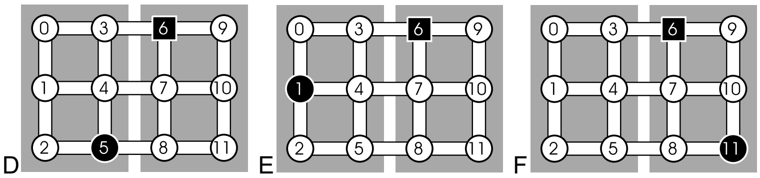

*Figure 8.* The rectangular test-routes. The black square and circle represent start- and target-place, respectively. While type D and type E routes both cross the region boundary, type F routes stays within a region. Type D and type E routes differ in the orientation of the long leg with respect to the region boundary.

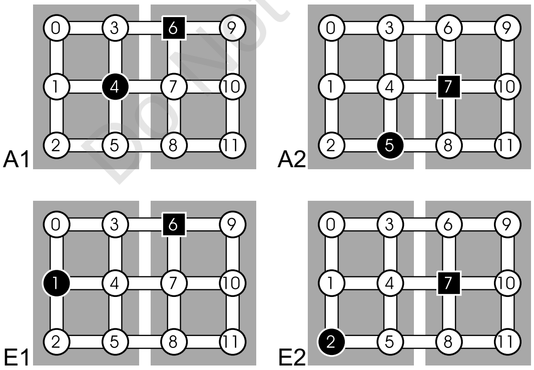

*Figure 9.* The variants of type A and type E routes. By shifting the start and target places about one grid point downward, we created variants of type A and type E routes with the same spatial configuration of start and target places but different absolute positions. These variants were designed to control for possible border effects.

Table 1:
*Here for each route type all single test routes are listed. The numbers correspond to the places in the virtual environment. Note that type B,C and D routes provided 4 test routes only, that were repeated in each of the two experimental blocks.*

| 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 |

## 4.3 Predictions & Variable of Interest

The hypotheses discussed in section 3.6 lead to different predictions for the navigation behaviour 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.

*H1 - Distorted Representation.* The 'Distorted Representation' hypothesis does not predict any systematic effect. Since subjects had to cross only one region boundary on all optimal alternative routes, an over-represented region boundary does not result in alternatives with different length. This is in contrast to Experiment 1, in which the alternative routes crossed different numbers of region boundaries. This hypothesis predicts that subjects choose to cross the region boundary sooner rather than later in 50% of the navigations.

*H2 - Persistence.* The Persistence strategy predicts that subjects stay in their current region as long as possible. That is to say, subjects prefer routes that allow to avoid the crossing of region boundaries as long as possible.

*H3 - Hierarchical Planning.* The *Hierarchical Planning* hypothesis proposes that subjects plan towards the target region rather than towards the target place. Not until entering the target region do subjects plan the rest of the route. This strategy predicts that subjects approach the target on the route that allows for fastest access to the target region.

*Variable of Interest.* As pointed out above, the different strategies predict different navigation behaviour 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 each route type that crossed a region boundary, we evaluated 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.

## 4.4 Statistical Analysis

See section 3.3 for details on the analysis.

## 4.5 Participants

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

## 4.6 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 (male: 1.25 errors; females: 3.21 errors; Wilcox rank sum test: p = 0.028).

### 4.6.1 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 routes. While female subjects navigated correctly in 90% of the trials, male subjects reached 95.3% correct navigations (Wilcox rank sum test: p = 0.08). In order to reduce noise we evaluate error-free navigations only.

*Regions effects.* By pooling across type A,B,C,D and E routes (see Figure 7 and Figure 8) we evaluated, for all route types with starting- and target-places in different regions, 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 = 0.0001, see Figure 10). 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 = 0.11, see Figure 10). Female and male subjects did not differ in their preference for routes that allow for fastest access to the target region (male 71.4% crossing, female 71.2% crossing).

*Rectangular test routes.* In contrast to the square test routes, the rectangular test routes have sides with different length (see Figure 8). 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. We evaluated whether subjects showed a preference to first navigate the long leg or the short leg, respectively (see Figure 12). With their first movement decision subjects followed the long leg of the route in 54.1% of the navigations (Wilcoxon signed rank test

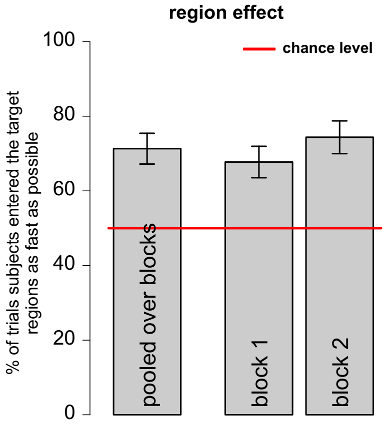

*Figure 10.* Subjects preference to enter the target region sooner rather than later for all route types with starting place and target place in different regions (type A,B,C,D,E routes). The left bar displays subjects preference pooled over experimental blocks, while the remaining bars displays subjects preference for the experimental blocks separately.

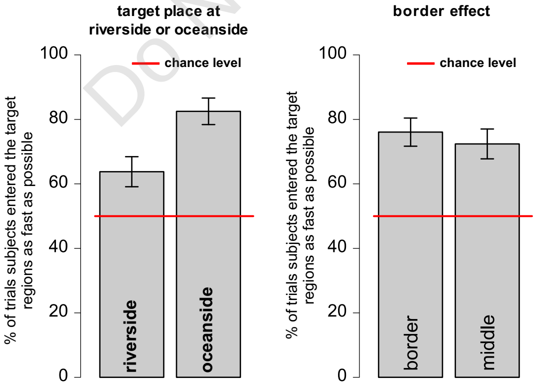

*Figure 11.* left: Subjects preference to enter the target region sooner rather than later for routes with target places at the riverside and at the oceanside; right: Subjects preference to enter the target region sooner rather than later for routes with starting places at the border of the environment or with starting places within the environment.

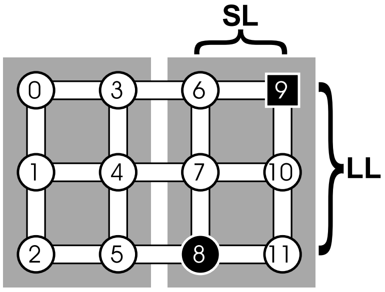

*Figure 12.* The rectangular type F routes do not cross the region border (LL = long leg, SL = short leg). From the starting place (place 9), subjects can decide to go to place 10 (following the long leg) or to go to place 6 (following the short leg).

against chance level (50%): $p = 0.35$). That is to say, we did not find a systematic influence of the rectangular shape of type F routes on human route planning.

*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 differentiated into routes that had the target place located at the riverside (target place was 3,4,5,6,7,8; see TYPE A, C and D routes in Figure 7 or Figure 8, respectively) and routes that had the target place at the oceanside of the environment (target place was 0,1,2,9,10,11; see TYPE B and E routes in Figure 7 or Figure 8, 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: $p < 0.001$, see Figure 11), 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%: $p < 0.01$ and $p < 0.001$, respectively).

*Border effects.* A comparison of the two optimal solutions of e.g., type A1 routes (see Figure 9) shows a striking difference between these alternatives. The route along the the border of the environment (along the places 6,3,4) provides less possible movement decisions than the alternative solution (along the places 6,7,4). This difference results from the T-junction at 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 E1 against routes of type A2 and E2 (see Figure 9), we separate this possible border effect 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: $p = 0.46$, see Figure 11). We could not find evidence for an influence of routes with different complexity on route planning behaviour.

## 4.7 Discussion

When navigating routes with starting- and target-place in different regions, subjects reliably preferred routes that allowed for fastest access to the target region above alternative routes. We have not found that the border of the virtual environment or the different complexity of alternative routes, respectively, influenced subjects navigation behaviour. 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 when navigating rectangular routes, subjects prefer to first navigate the long leg rather than the short leg.

Having ruled out these navigation strategies, we conclude that the observed effect really is due to the regions we 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 predicts that subjects choose a target region first, and then plan their route in order to access the target-region as fast as possible (see section 4.3). Such a planning algorithm would lead to the navigation behaviour observed during the experiment.

Depending on the position of the target place in the target-region the magnitude of the ‘region effect’ is 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 our 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 (also described as gateways by Chown et al., 1995) 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 allows for direct transfer to the target place. This might explain the weaker effect found for routes with targets at the riverside.

## 5 General Discussion

We have presented two experiments that revealed an influence of environmental regions on human route planning and navigation behaviour. In Experiment 1 we have shown that subjects minimize the numbers of region boundaries they pass by during a navigation. We have offered three alternative hypotheses that could account for the observed effect. Experiment 2 was designed to discriminate between these hypotheses and showed that subjects entered regions containing a target 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 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. Illustration *a* of Figure 13 represents such a hierarchical reference memory of the virtual environment used in Experiment 1.

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 normally vaguely defined, as recently pointed out by Montello, Goodchild, Gottsegen, and Fohl (2003). Additionally, regions as represented in spatial memory might overlap. For our analysis we have assumed that subjects represented the regions we had introduced in the environments as such in their spatial memory. Indeed most subjects in Experiment 1 and all subjects in Experiment 2 reported in the debriefing sessions that they had perceived the regions we had introduced; subjects who did not perceive the different regions in Experiment 1 did not show any ‘region effect’. However, we can not rule out, that subjects represented the regions somewhat differently.

According to the complexity of the environment and according to the number of targets, route planning can be a very complex task. Planning algorithms that take into account the hierarchies of spatial representations, usually use the abstraction of spatial information at higher levels to reduce the complexity of a given planning task.

For example, in “Traveller”, a computational model for learning spatial networks (Leiser & Zilbershatz, 1989), routes to targets in distant regions are planned by decomposing the search for a route into three sub-problems: (i.) from the start location to the starting region’s centroid, i.e., an often visited and well known

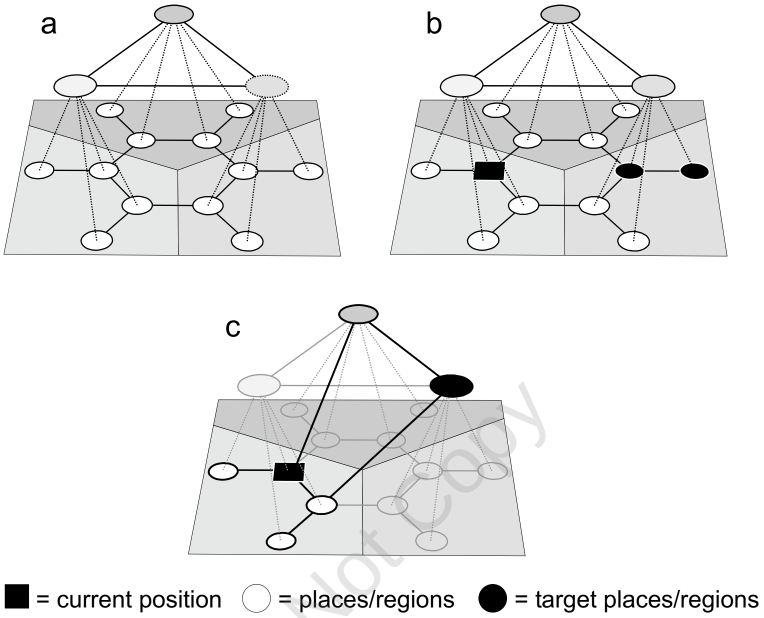

*Figure 13.* Generating a focal representation from hierarchical reference memory, current ego-position and targets: Illustration a represents the hierarchically organized reference memory of the virtual environment used in Experiment 1. In illustration b an observer (black rectangle) is placed at a 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.

place within that region [1]; (ii.) from the centroid of the starting region to the centroid of the target region; and (iii.) from the centroid of the target region to the target location.

In *coarse-to-fine* route planning, as e.g., proposed by Chown et al. (1995), first a coarse plan using higher levels of the spatial representation is generated. Plans formed at such 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. This *coarse-to-fine* planning algorithm is a representative of a larger class of hierarchical planning schemes which is consistent with our data.

*A cognitive model of 'Hierarchical Route Planning'.* The sketched *coarse-to-fine* algorithm assumes 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. This algorithm has a large memory load while the processing effort is rather low. However, if we assume that processing may go on with navigation, an algorithm with low memory load and higher processing load would appear rather more attractive. Here we present an alternative model where steps are only planned one at a time and the memory load is minimized. The algorithm relies on a working memory stage containing a detailed representation at the current position and a coarse representation of distant locations. We therefore call it 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 coarse-space information for distant locations exclusively. We refer to such representations 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 13. Note that in *focal representations* places in one 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-odinate 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.

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

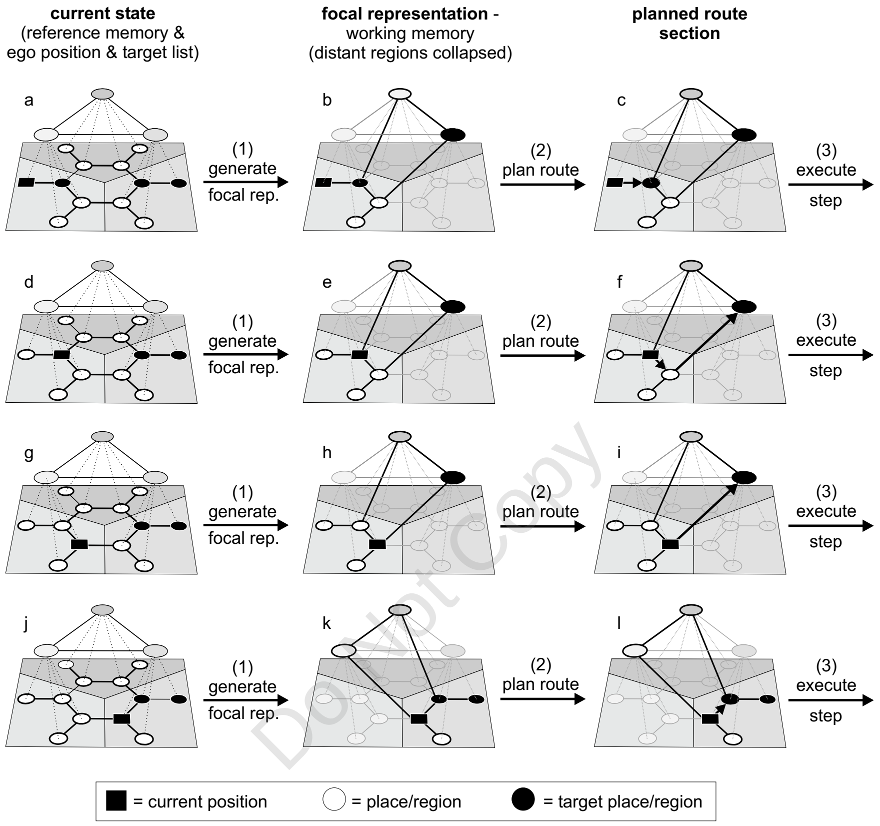

*Figure 14.* Fine-to-coarse route planning. left column: current state of the navigation task, superimposed on the spatial reference memory; middle column: focal representation, i.e., working memory used for planning (spatial information at different levels-of-detail is used simultaneously); right column: 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 13. Operation (2) route planning. Operation (3) traveling a route section and restart of planning cycle.

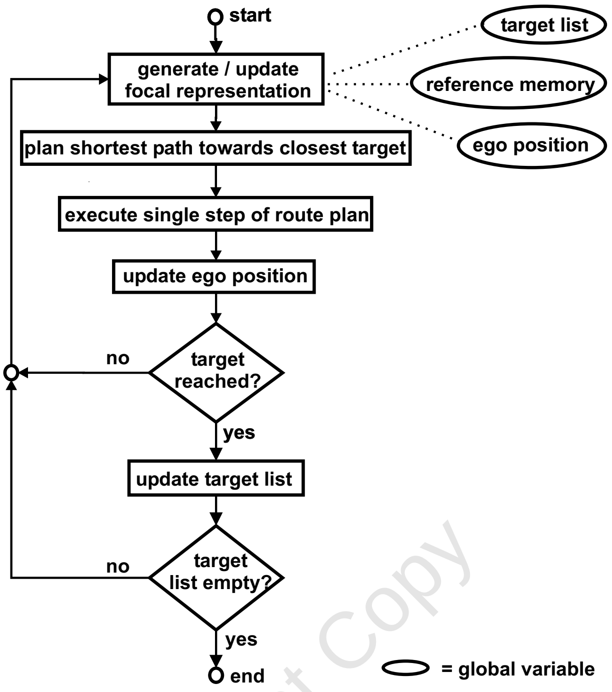

*Figure 15.* A generic flow chart of the *fine-to-coarse* planning heuristic.

Figure 14 and the flow chart in Figure 15 demonstrate the *fine-to-coarse* planning heuristic in detail for one of the test routes used in Experiment 1 (see type A routes in Figure 3). 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 region, 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 replan 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.

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