Route navigating without place recognition:
What is recognised in recognition-triggered responses?

Hanspeter A Mallot, Sabine Gillner¶
Max-Planck-Institut für biologische Kybernetik, Spemannstrasse 38, D 72076 Tübingen, Germany;
e-mail: hanspeter.mallot@tuebingen.mpg.de
Received 30 October 1998, in revised form 20 August 1999

Abstract. The use of landmark information in a route-navigation task has been investigated in a virtual environment. After learning a route, subjects were released at intermediate points along the route and asked to indicate the next movement direction required to continue the route. At each decision point, three landmarks were present, one of which was viewed centrally and two which appeared in the periphery of the visual field when approaching the decision point. In the test phase, landmarks could be replaced either within or across places. If all landmarks combined into a new place had been associated with the same movement direction during training, subjects performed as in the control condition. This indicates that they did not need to recognise places as configurations of landmarks. If, however, landmarks that had been associated with conflicting movement directions during training were combined, subjects' performance was reduced. We conclude that local views and objects are recognised individually and that the associated directions are combined in a voting scheme. No evidence was found for a recognition of places as panoramic views or configurations of objects.

1 Introduction
One important source of information for navigation and spatial memory is provided by the external sensory signals obtained instantaneously at each position in space. This 'local position information', ie the manifold of all sensor readings as a function of observer position and orientation, is the most general concept of allocentric, or landmark information. In vision, the local position information at one particular point is a view or 'snapshot', ie a raw image.

Landmark information can be used in a number of different ways. We give a brief overview in terms of two largely independent dimensions: (i) the amount of image processing needed to extract the landmark from the sensory input, and (ii) the function of a landmark in spatial behaviour.

(i) Virtually no image processing (except, maybe, for normalisation or bandpass filtering) is required in snapshot-based schemes (eg Cartwright and Collett 1982). Remembering only the pattern of black and white spots in an image without any higher-level processing such as object recognition is already sufficient for a large number of navigation tasks; see Schölkopf and Mallot (1995) and Franz et al (1998a) for a view-based approach to cognitive maps. However, there is evidence for more sophisticated image processing being involved in mammalian navigation behaviour. Cheng (1986), in rodents, and Hermer and Spelke (1994), in young children, have found that geometric information in images is a stronger cue than pure texture or contrast information. This indicates that some image processing has taken place to recover geometrical, ie depth, cues from the images. Another image-processing operation, the segmentation of the image into objects and the assignment of depth values to these objects is assumed in some theoretical approaches, eg by Zipser (1985), O'Keefe (1991), Penna and Wu (1993), or Prescott (1996). Landmark selection may also be based on their location at

¶ Present address: Abteilung Unfallchirurgische Forschung und Biomechanik, Universität Ulm, Helmholtzstrasse 14, D 89081 Ulm, Germany; e-mail: sabine.gillner@medizin.uni-ulm.de

bifurcations or other critical sections of a route (Cohen and Schuepfer 1980; Aginsky et al 1997). In summary, various types of landmark information ranging from snapshots to identified objects may coexist in biological navigation systems.

(ii) The second dimension along which types of landmarks can be distinguished is landmark function. O'Keefe and Nadel (1978) distinguish guidance and direction, the latter of which is now usually referred to as 'recognition-triggered response' (Trullier et al 1997)—see figure 1. In guidance, movement is such that a certain configuration of landmarks is obtained. In the simplest case, this is just the central approach towards a landmark which is then often called a beacon. By keeping the image of a distant landmark at a fixed retinal position, straight walks over short distances (compared with the distance to the landmark) and with arbitrary direction can be produced; here, the global landmark provides some sort of compass information. A more general example of a guidance would be to move to a place where one landmark is straight-ahead of the observer, a second is 90° to the left, and a third landmark is 90° to the right. By this token, guidance can be used to reach arbitrary places in open space. Examples include the Morris water maze task in rodents (Morris 1981), scene-based homing in insects (Cartwright and Collett 1982), and human place learning in virtual space (Jacobs et al 1998). In terms of the image-processing classification, Cartwright and Collett (1982) suggest a snapshot scheme (see also Franz et al 1998b for a survey of scene-based homing schemes).
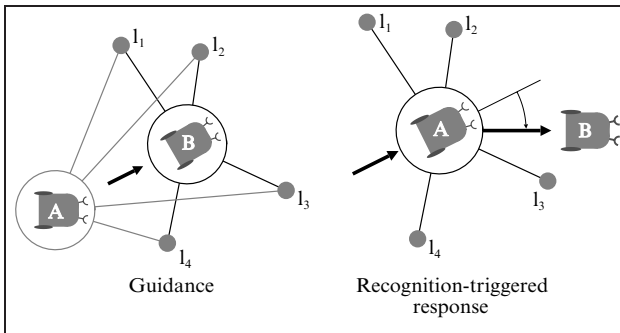

Figure 1. Two types of landmark function. The circles surrounding the vehicles symbolise the visual array of the respective position; l_1, ..., l_4 are landmarks. In *guidance* (left), the 'snapshot' visible at position B has been stored. At a location A, movement is such that the currently visible snapshot will become more similar to the stored one. In *recognition-triggered response* (right) memory contains both a snapshot and an action associated with it. When the snapshot is recognised in A, an action such as a turn by some remembered angle is executed.

In guidance, spatial memory contains a desired snapshot or landmark configuration. The movement required to reach the place corresponding to this configuration is computed by comparing current and stored landmark positions. In recognition-triggered response, memory contains also a second bit of information, namely an action to be performed when a place is reached, ie when a landmark configuration is recognised.

In the definition given by Trullier et al (1997), the term 'place-recognition-triggered response' implies that place recognition is independent of the observer's orientation or viewing direction, and that, prior to actually taking the local action, a standard orientation with respect to the place has to be obtained each time the observer comes back to the place. Alternatively, one could assume a view-recognition-triggered response, in which views, rather than places, are recognised. In honey bees, Collett and Baron (1995) have shown that movement decisions can in fact be triggered by recognition of views.

In a previous paper (Gillner and Mallot 1998) we have presented evidence for recognition-triggered responses in human subjects navigating through a virtual environment.

It was shown that subjects returning to a given landmark are biased towards repeating the movement performed when last passing along that same landmark. This persistence seems to be independent of the currently pursued goal. While this behaviour is rather stereotyped and may be classified as route knowledge, evidence of configuration knowledge and cognitive maps is simultaneously present in the same subjects. For a detailed discussion of the relation of route knowledge and configuration knowledge in a unified framework (the view-graph approach) see Gillner and Mallot (1998) and Schölkopf and Mallot (1995).

What exactly is recognised in recognition-triggered responses: views or places? For the case of guidance, Poucet (1993) has argued that local views are mentally integrated into panoramic views which serve as a representation of the respective place. This representation will be independent of each local view and the observer's viewing direction. A similar conclusion has been drawn by Jacobs et al (1998) who had subjects find a place in a simulated arena surrounded by structured walls. In the recognition part of a recognition-triggered response, independence of observer orientation is not desirable, at least if the action triggered by recognition is a turning movement. If recognition were in fact independent of orientation, additional compass information would be required as a reference for such directional movements. In this paper, we ask whether the recognition part of a recognition-triggered response concerns (i) individual objects or views of objects, or (ii) a landmark configuration or panoramic view of a place. The role of compass information, which would be required if actions were triggered by recognised places, but not if they were triggered by recognised views, has been addressed elsewhere (Steck and Mallot 2000).

We investigate the question of view-based or object-based versus place-based direction memory by means of landmark transposition experiments in the 'Hexatown' virtual environment (see Gillner and Mallot 1998, and section 2). The possibility of manipulating the environments by exchanging landmarks, illumination, or the positions of occluders is one of the biggest advantages of virtual-reality technology (see van Veen et al 1998). The relation of experiments done in real and virtual environments has recently been reviewed by Péruch and Gaunet (1998).

2 The Hexatown environment

A virtual town was constructed with the aid of Medit software and animated with a frame rate of 36 Hz on an SGI Onyx RealityEngine with IRIX Performer software. A schematic map of the town appears in figure 2. It is built on a hexagonal raster with
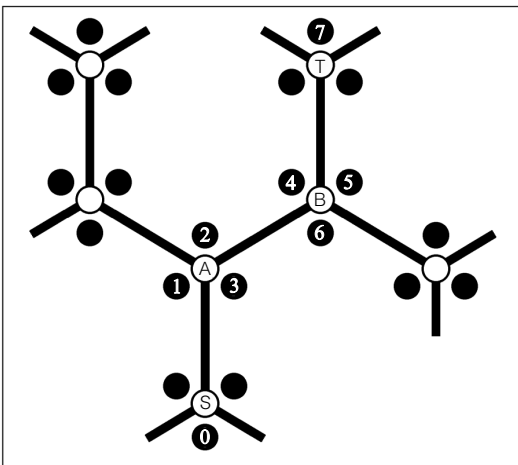

Figure 2. Street map of the virtual maze with 7 places and 21 views. The views numbered 1–6 are the ones used for the landmark transposition experiments. S (view 0) marks the start and goal for the route being learnt; T (view 7) marks the turning point. Excursions to the unnumbered places are allowed in the exploration phase but are counted as errors in the later phases of the experiment.

a raster length (distance between two places) of 100 m. At each junction, one object, normally a building, was located in each of the 120° angles between the streets; so each place consisted of three objects. In the places with less than three incoming streets, dead ends were added instead, terminating with a barrier at about 30 m. The hexagonal layout was chosen to make all junctions look alike. In comparison, Cartesian grids (city-block raster) have the disadvantage that long corridors are visible at all times and the possible decisions at a junction are highly unequal: going straight to a visible target or turning to something not presently visible. The whole town was surrounded by a distant circular mountain ridge which did not provide landmark information. It was constructed from a small model which was repeated every 20°.

Subjects could move about the town using a computer mouse. In order to have controlled visual information and not to distract subjects' attention too much, movements were restricted in the following way. Subjects could move along the street on an invisible rail right in the middle of each street. This movement was initiated by hitting the middle mouse button and was then carried out with a predefined velocity profile without further possibilities for the subject to interact. The translation took 8.4 s with a fast acceleration to the maximum speed of 17 m s^{-1} and a slow deceleration. The movement ended at the next junction, in front of the object facing the incoming street. Similarly, turns could be performed in steps of 60° by pressing the left or right mouse button. Again, the simulated movement was 'ballistic', ie following a predefined velocity profile. Turns took 1.7 s with a maximum rate of rotation of 70° s^{-1} and symmetric acceleration and deceleration. Viewing direction was not controlled in our experiments.

Figure 3 shows the movement decisions that subjects could choose from. Each transition between two views is mediated by two movement decisions. When facing an object (eg the one marked a in figure 3), 60° turns left or right (marked L, R) can be performed which will lead to a view down a street. If this is not a dead end, three decisions are possible: the middle mouse button triggers a translation down the street (marked G for go), while the left and right buttons are used to execute 60° turns. If the street is a dead end, turns are the only possible decision. In any case, the second movement will end in front of another object.

An aerial view of Hexatown is shown in figure 4. Central views of the buildings playing a role in the experiments appear in figure 5.

A circular hedge or row of trees was placed around each junction with an opening for each of the three streets (or dead ends) connected to that junction. This hedge looked the same for all junctions. It allowed viewing of the objects facing the streets
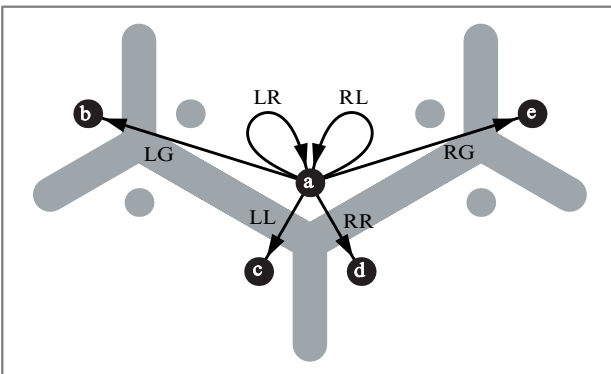

Figure 3. Possible movement decisions when facing the view marked a. L: turn left 60°. R: turn right 60°, G: go ahead to next place. Note that the arrows illustrate the sequence of views generated by each pair of movement decisions, not the paths travelled by the subject.
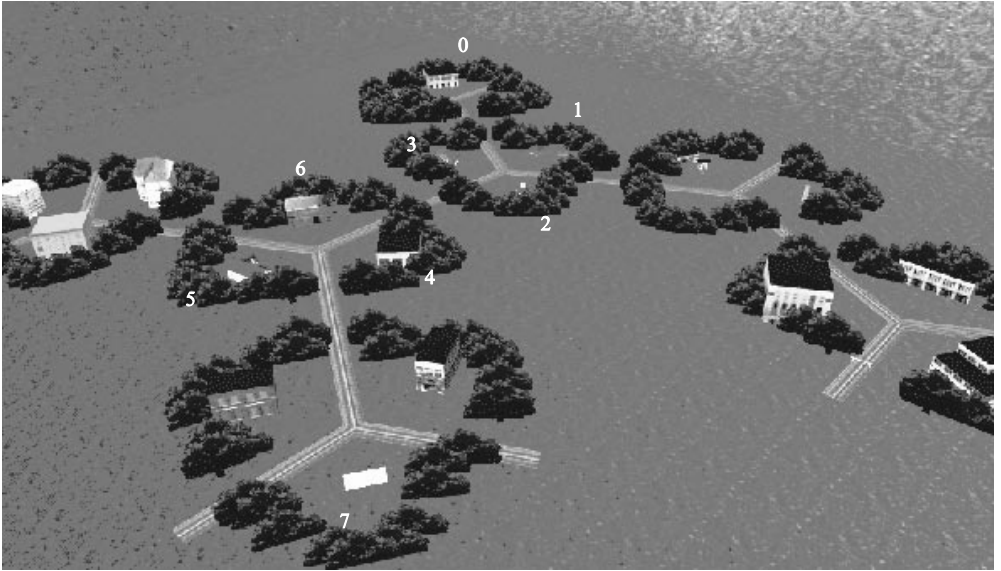
Figure 4. Aerial view of Hexatown. Note that the orientation is different from that of the street map in figure 2. The numbers on the black background are the view numbers. The aerial view was not available to the subjects. Object models are courtesy of Silicon Graphics Inc. and Professor F Leberl, Graz.
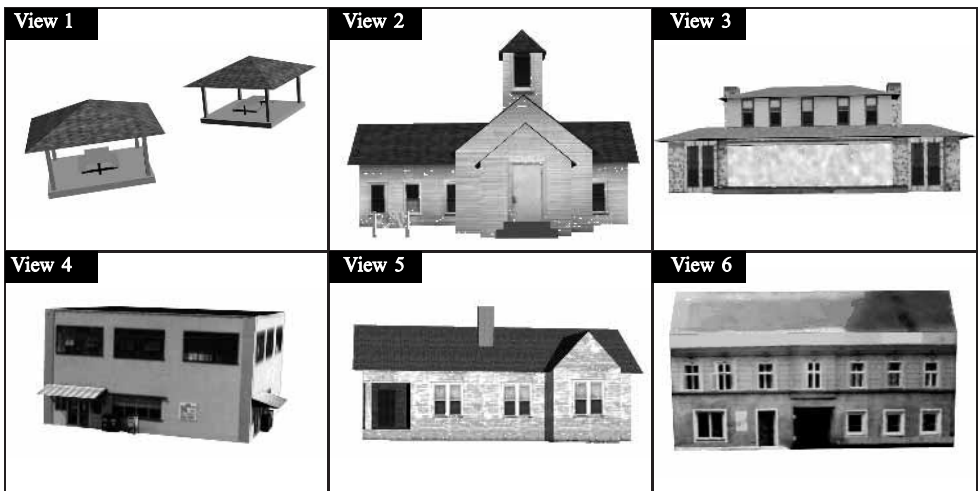

Figure 5. Frontal views of some objects used as landmarks in the Hexatown environment. The objects were located at places A and B in the maze (see figures 2, 4) and could be exchanged during the experiments.

emanating from the junction where the observer was currently located while all other buildings at distant junctions were occluded. The buildings were at a distance of 15 m from the junction; all three buildings were seen at once on passing the hedge and entering the place. The simulated field of view was 60 deg. Illumination was simulated from the bright sky. Taken together, the visibility parameters were the same as in viewing condition 3 of Gillner and Mallot (1998).

3 Rationale of the experiments

In recognition-triggered responses, recognition might apply to places or to local views. A place is defined either as a configuration of landmarks (structural description) or as the panoramic view visible from the place in question. A local view covers only a fraction of the visual array and its recognition does not necessarily imply the simultaneous recognition of the entire place where the local view occurred. In order to distinguish between these two possibilities, we designed an experiment to resolve whether recognition-triggered response implies recognition of the place where this response occurred. We trained subjects to learn one particular route in the town as a chain of recognition-triggered responses. The route is marked by the letters $S \rightarrow A \rightarrow B \rightarrow T \rightarrow B \rightarrow A \rightarrow S$ in figure 2. After training, individual landmarks were replaced in a number of different ways. These exchange conditions were chosen such that the recognition of places and views were affected to different degrees.

We illustrate the exchange conditions used for the approach of view 5 in place B (see figure 6). In all cases, the central view, view 5, would remain unchanged. Four exchange conditions were used in the experiments:

C1: *control*. No exchanges were done here.

C2: *within place*. Exchange of left and right peripheral views (ie $4 \leftrightarrow 6$). In the training phase, view 6 was either in the right or the central position; its occurrence on the left side after mirroring does not therefore provide clear information. For view 4, the situation is different: it occurred either on the left or the right side during training and correct turns were always in the direction of its position. Therefore, the information provided by view 4 after mirroring is in conflict with the information provided by the central view 5.

C3: *across places, consistent*. The peripheral views were replaced by views from another place associated with the same motion decision during training. For the approach of view 5, this means that view 4 (left visual field) is replaced by view 3, which has been associated with a left turn when appearing in the left visual field. View 6 (right visual field) is replaced with view 2, whose appearance in the right visual field was also associated with a left turn during training.

C4: *across places, inconsistent*. As condition C3 above, but this time the central view and the replacement views have been associated with different movement decisions during learning. The replacement is: $4 \leftrightarrow 1$ and $6 \leftrightarrow 3$.

The view numbers mentioned above apply to the approach of view 5 in place B. For a complete list of replacements, see table 2.

The exchange conditions C1 – C4 affect the place or scene at which a movement decision has to be taken, to various amounts. In particular, four hypotheses concerning the stored place representation and the correspondingly expected outcome can be formulated:

H1: *landmark configuration (structural description or panoramic view)*. Spatial memory could involve a structural description of places containing information on the full landmark configuration at each place. If movement decisions are triggered by recognition of these landmark configurations, performance should go down to chance level in exchange conditions C2, C3, and C4, since the landmark configuration is affected in all these conditions.

H2: *set of landmarks*. A place could be remembered by the set of landmarks defining it, irrespective of their configuration. In this case, we expect performance to be high in conditions C1 and C2, while performance should drop to chance level in conditions C3 and C4.

H3: *frontal view only*. If memory contains only frontal views, performance should be equally high in all exchange conditions.
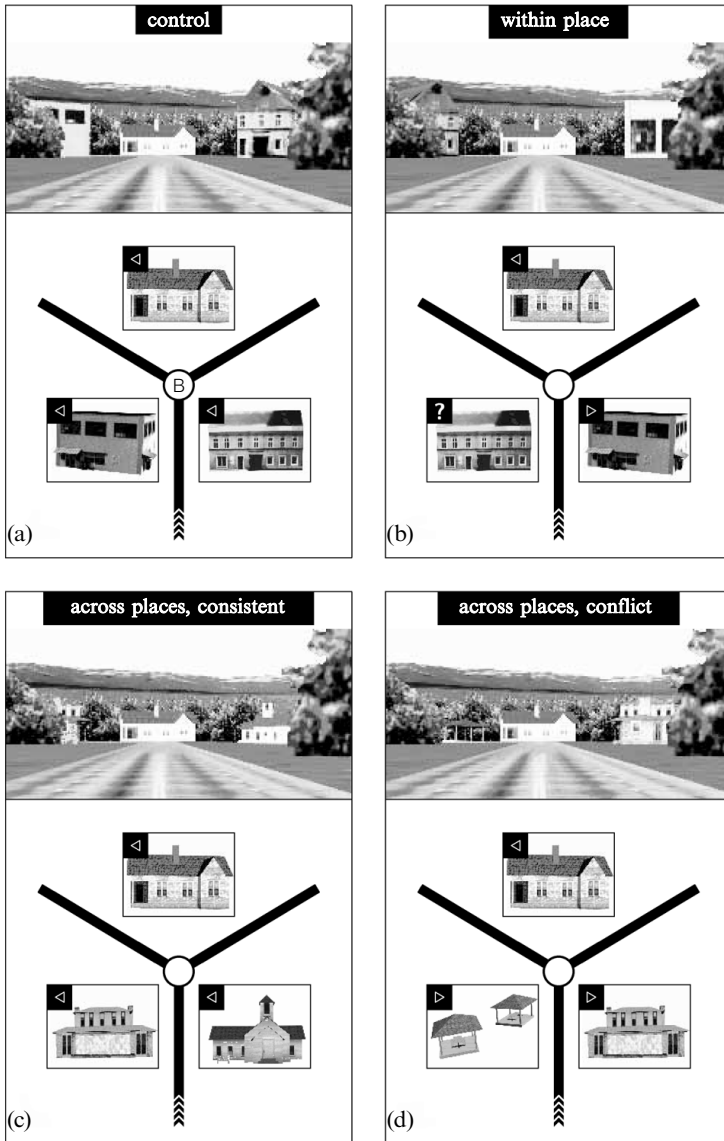
Figure 6. Exchange conditions used in the experiments. For illustration, the approach A → B is shown (release condition R3). ◁: This view in the current position has been associated with left turns during learning. ▷: same for right turns. ?: object did not occur in this position during training. (a) *Control condition without exchange.* The place can be recognised as place B and the movement associated with all individual views is left. (b) *Exchange of peripheral landmarks within place.* Both place recognition and view – movement associations might be affected. (c) *Consistent exchange across places.* Place recognition is affected but view – movement associations for all views are the same. (d) *Conflicting exchange across places.* Place recognition is affected and view – movement associations support different movement decisions.

H4: *landmark voting.* Finally, recognition might apply to views of individual objects, together with their position in the visual field. In this case, memory would contain items like "if view 2 is in the centre, turn right" or "if view 1 is to the left, turn right". In this case, we expect that condition C3 should lead to high performance since direction information from all views is unanimous. In contrast, in condition C4 we expect a drop of performance to some level determined by the respective confidence given to the

individual movement votes. In the mirroring condition C2, a small drop in performance can be expected since one of the exchanged landmarks (the right one in figure 6b) changes it directional information during replacement and is thus in conflict with the central view.

The expected experimental outcome for each of these four hypotheses is summarised in table 1.

Table 1. Expected performance in the exchange experiment for four possible hypotheses of place and view recognition (H1 – H4).

	C1: control	C2: within place	C3: consistent	C4: conflict
H1: landmark configuration	max.	chance	chance	chance
H2: set of landmarks	max.	max.	chance	chance
H3: frontal view only	max.	max.	max.	max.
H4: landmark voting	max.	slight reduction	max.	reduced

4 Procedure

Experiments were performed on a standard SGI monitor with a 19 inch visible image diagonal. Subjects were seated comfortably in front of the screen and no chin-rest was used. They moved their heads in a range of about 40 to 60 cm in front of the screen which results in a viewing angle of about $35 - 50$ deg.

The experiments were run on forty-three paid volunteers who were students at the University of Tübingen. Three participants realised and reported the landmark replacements. Their data have been excluded from the evaluation.

4.1 Experiment 1

The experiment was performed in three phases. In phase 1, subjects were released facing view 0 (see figure 2). A printout of the view marked 7 in figure 2 was given to the subjects and they were instructed to learn the shortest possible way from 0 to 7 and back to 0. Path length was defined as the number of mouse clicks or movement decisions, where turns are taken into account. In this first phase of the experiment, subjects were allowed to explore the entire maze, ie they could leave the route. This phase was terminated when the shortest possible route was found for the first time.

In the second phase of the experiment, subjects were released at one of four positions along the route and transport towards the adjacent place was simulated. This transport was a pure translation without turns. The release conditions were (see also figure 7a):
R1: S → A (2): Release at place S and movement towards place A, facing view 2.
R2: B → A (1): Release at place B and movement towards place A, facing view 1.
R3: A → B (5): Release at place A and movement towards place B, facing view 5.
R4: T → B (6): Release at place T and movement towards place B, facing view 6.
In all cases, subjects were asked to continue the route initiated by the approach until reaching either place S or place T, whichever was reached first. This phase of the experiment was repeated if the initial decision after release was incorrect.

The third phase of the experiment was the actual test phase. Here, subjects were released as in the second phase. After completing the approach to the adjacent place, they had to decide whether the correct route continued left or right. As always, movement decisions were performed by clicking the appropriate buttons of the computer mouse. In this test phase, however, no feedback was given to the subjects; ie after subjects' decision left or right, the trial was terminated.

For each subject, 16 decisions were recorded corresponding to the 4 exchange conditions multiplied by the 4 release conditions (table 2). The sequence of decisions used for half of the subjects was (R4|C1), (R3|C1), (R2|C2), (R1|C4), (R4|C3), (R1|C1), (R3|C4), (R1|C3), (R3|C3), (R2|C4), (R4|C2), (R1|C2), (R4|C4), (R2|C3), (R3|C2),
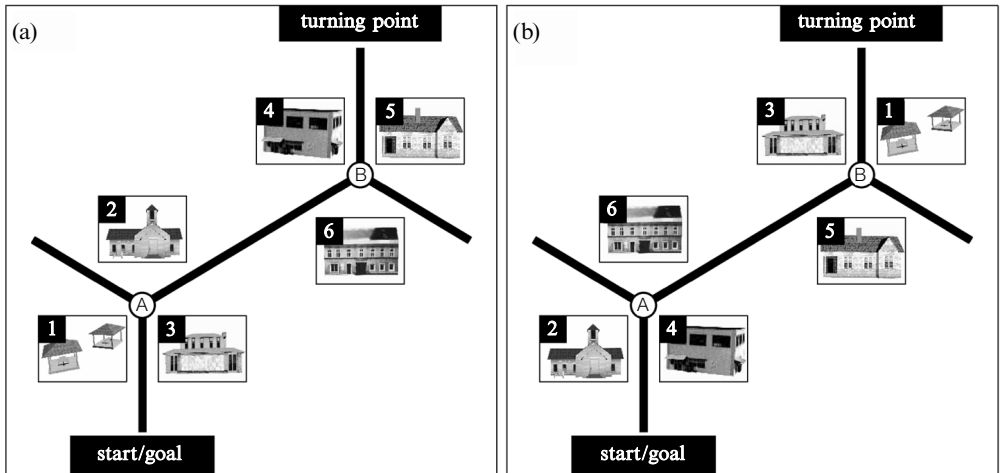
Figure 7. Landmark configuration in the training phase. (a) Initial landmark layout used in experiment 1. (b) Reshuffled landmark layout used in experiment 2.

Table 2. Overview of tests performed during the third phase of experiment 1. R1–R4: release conditions. C1–C4: conditions of landmark exchange. Approach direction is from below. For the control condition (left column), the letters A and B mark the decision place and the correct movement decision is given in the lower right corner.

(R2|C1). For the other half of the subjects, the reverse sequence was used. This sequence was put together such that the release positions in subsequent trials were always different. No differences between the results from this sequence and the reverse sequence were found. The data will therefore be presented together.

4.2 *Experiment 2 (control)*

The experiment was repeated with a second group of subjects with a different initial arrangement of landmarks. With this control experiment, we attempted to account for effects of landmark positioning and differences in landmark salience. Experiment 2 was

identical to experiment 1 except for the initial arrangement of the landmarks, which appears in figure 7b. The release conditions for experiment 2 were:

R1: S → A(6): Release at place S and movement towards place A, facing view 6.
R2: B → A(2): Release at place B and movement towards place A, facing view 2.
R3: A → B(1): Release at place A and movement towards place B, facing view 1.
R4: T → B(5): Release at place T and movement towards place B, facing view 5.

The exchange conditions follow the same logic as in experiment 1. They can be derived from table 2 by replacing the view numbers as indicated by figure 7.

5 Results

Altogether, forty-three subjects took part in the experiments. The first learning phase, which was terminated when the subjects had travelled the correct route without error for the first time, took 1 to 7 trials with an average of 2.6 trials. The number of wrong movement decisions (ie movements not reducing the number of mouse clicks needed to reach the goal) occurring during the entire learning phase varied between 0 and 60 with an average of 10.7. In the second training phase (completion of route from a release point) most tasks were solved in the first trial (average number of trials per task: 1.4). The highest number of repetitions necessary in the second phase was 4.

5.1 Experiment 1

The data from experiment 1 (original landmark configuration as shown in figure 7a) appear in figure 8. In the histogram, in the upper part, each column corresponds to one of the 16 test conditions listed in table 2. The height of each column shows the number of subjects choosing the correct movement decisions, ie the movement decision suggested by the centrally viewed object. Twenty-two subjects participated in this experiment, two of whom reported a change in landmark configuration in the test phase. These two subjects were excluded from the analysis. An analysis of variance (ANOVA, 4 exchange conditions × 4 release conditions × 2 sequence conditions) shows significant main effects of exchange condition ($F_{3, 54} = 3.61$, $p = 0.019$) and release
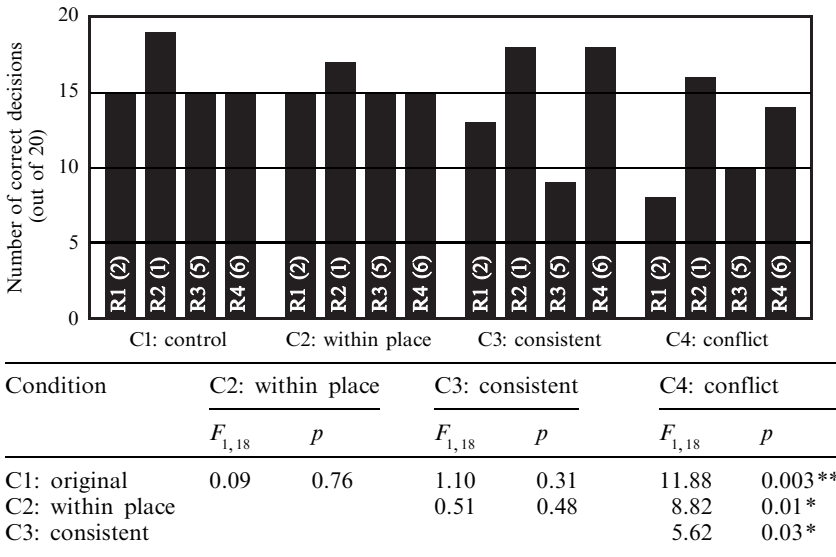

Condition	C2: within place		C3: consistent		C4: conflict	
	$F_{1, 18}$	p	$F_{1, 18}$	p	$F_{1, 18}$	p
C1: original	0.09	0.76	1.10	0.31	11.88	0.003**
C2: within place			0.51	0.48	8.82	0.01*
C3: consistent					5.62	0.03*

Figure 8. Results from experiment 1 (original landmark arrangement). (Top) Number of correct decisions (in the sense of the centrally presented object). R1–R4: release condition; the number in brackets is the number of the central view. (Bottom) Analysis of variance of number of correct decisions as a function of exchange condition. Data in condition C4 (conflict) differ significantly from the other conditions.

condition ($F_{3,54} = 3.70$, $p = 0.017$). The sequence of tasks had no significant effect ($F_{1,18} = 0.044$, $p = 0.84$).

The first four columns of figure 8 show the control condition where no exchanges had been done. In this condition, 80% of the decisions were correct. Exchanging landmarks within one place (condition C2) had almost no effect. Consistent exchanges across places (condition C3) led to a reduction of the fraction of correct decisions to 73%, which, however, was not significant (see lower part of figure 8). Conflicting changes across places (condition C4) reduce the fraction of correct decisions to 60%. As is shown by the analysis of variance in the lower part of figure 8, condition C4 differs significantly from all other conditions, whereas the pairwise differences between conditions C1, C2, and C3 are not significant.

The differences between the columns within one exchange condition reflect different saliences of the central landmarks. If view 1 appears in the centre (release condition R2), subjects are more likely to decide in agreement with this central view. Conversely, view 2 is often outvoted by the peripheral views.

5.2 Experiment 2 (control)

In order to control for possible effects of the initial placement of landmarks, we repeated the experiment with the same landmarks arranged at different positions from the beginning of the experiment (figure 7b). Twenty-one subjects took part in this experiment, one of whom reported changes of landmark configuration in the test phase. Again, this subject was excluded from further analysis. An analysis of variance (ANOVA, 4 exchange conditions × 4 release conditions × 2 sequence conditions) shows significant main effects of exchange condition ($F_{3,54} = 4.57$, $p = 0.009$) and release condition ($F_{3,54} = 4.08$, $p = 0.010$). The sequence of tasks had no significant effect ($F_{1,18} = 1.93$, $p = 0.18$).

The results from experiment 2 appear in figure 9. Presentation is as in figure 8. Note that the relation of release condition and centrally viewed landmark has changed owing to the landmark reshuffling. The results are well in line with those from experiment 1. As can be seen from the analysis of variance (lower part of figure 9), results in the
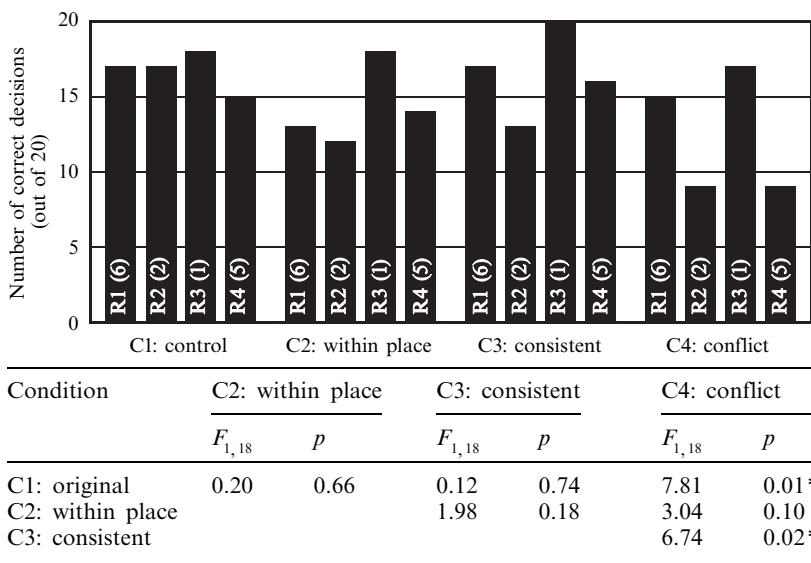

Condition	C2: within place		C3: consistent		C4: conflict	
	$F_{1,18}$	p	$F_{1,18}$	p	$F_{1,18}$	p
C1: original	0.20	0.66	0.12	0.74	7.81	0.01*
C2: within place			1.98	0.18	3.04	0.10
C3: consistent					6.74	0.02*

Figure 9. Results from experiment 2 (reshuffled landmark arrangement). (Top) Number of correct decisions (in the sense of the centrally presented object). (Bottom) Analysis of variance of number of correct decisions as a function of exchange condition. Data in condition C4 (conflict) differ significantly from the other conditions.

conflict condition (C4) differ significantly from the results in conditions C1 and C3, whereas differences between conditions C1, C2, and C3 are not significant. Performance in condition C2 is slightly reduced and the difference between conditions C2 and C4 is not significant. Again, view 1 (now in release condition R3) leads to more correct decisions than view 2.

6 Discussion

The results indicate that recognition-triggered response does not rely on structural descriptions or panoramic representations of places. The structure of places and even the selection of buildings making up a place can be destroyed without affecting recognition-triggered response. The only condition where a significant effect was found involved a novel combination of views (buildings) associated with conflicting directions during training. This result is consistent with the hypothesis of 'landmark voting', but not with any of the other hypotheses formulated in section 3. The slight reduction in performance found for exchange condition C2 in experiment 2 may also be expected from the landmark-voting hypothesis, since some conflict is involved in this condition as well. We therefore conclude that individual buildings or the snapshots taken from these buildings are the recognised landmarks in recognition-triggered response.

This result is well in line with the view-graph approach to visual navigation developed by Schölkopf and Mallot (1995). It states that local views of the maze together with their adjacencies are a sufficient representation of space. In the view-graph, views are connected if they can occur in immediate temporal sequence when exploring the maze. Views occurring in one place are not treated differently from views occurring in adjacent places as long as the temporal sequence constraint is satisfied. In this sense, the notion of a 'place' does not exist in this view-based approach. Places can be recovered from the view-graph by more sophisticated analysis, however.

A view-based organisation of route memory is also well in line with electrophysiological findings from primate hippocampus, indicating that, in primates, hippocampal cells code for views, rather than places (Rolls et al 1998).

A second important result of the present study is that the directional votes of different views receive different weights. Directions associated with more salient views (such as the picknick huts of view 1) are more likely to be followed by the subjects. The same is true for view 6 (large greenish-yellow building) whereas views 2 and 5 seem to be less reliable. This effect remains after relocating all objects along the route (experiment 2), indicating that this salience depends on the objects themselves, not just on their position.

A third interesting result is that forty out of forty-three subjects did not report the landmark translocations. This is reminiscent of recent findings on change blindness (Simons and Levin 1997) where subjects fail to notice substantial changes to the currently watched scene. Note, however, that in our experiment change detection requires a comparison between the current scene and a scene encountered several minutes earlier. This scene is presumably represented in a long-term spatial memory, which makes our effect quite different from standard change blindness where working memory is affected. It should also be noted that we did not explicitly ask our subjects about possible scene changes after the experiment.

References

Aginsky V, Harris C, Rensink R, Beusmans J, 1997 "Two strategies for learning a route in a driving simulator" *Journal of Environmental Psychology* **17** 317 – 331

Cartwright B A, Collett T S, 1982 "How honey bees use landmarks to guide their return to a food source" *Nature (London)* **295** 560 – 564

Cheng K, 1986 "A purely geometric module in the rat's spatial representation" *Cognition* **23** 149 – 178

Cohen R, Schuepfer T, 1980 "The representation of landmarks and routes" *Child Development* **51** 1065 – 1071

Collett T S, Baron J, 1995 "Learnt sensori-motor mappings in honeybees: interpolation and its possible relevance to navigation" *Journal of Comparative Physiology A* **177** 287 – 298

Franz M O, Schölkopf B, Mallot H A, Bülthoff H H, 1998a "Learning view graphs for robot navigation" *Autonomous Robots* **5** 111 – 125

Franz M O, Schölkopf B, Mallot H A, Bülthoff H H, 1998b "Where did I take that snapshot? Scene-based homing by image matching" *Biological Cybernetics* **79** 191 – 202

Gillner S, Mallot H A, 1996 "Place-based versus view-based navigation: Experiments in changing virtual environments" *Perception* **25** Supplement, 93

Gillner S, Mallot H A, 1998 "Navigation and acquisition of spatial knowledge in a virtual maze" *Journal of Cognitive Neuroscience* **10** 445 – 463

Hermer L, Spelke E S, 1994 "A geometric process for spatial reorientation in young children" *Nature (London)* **370** 57 – 59

Jacobs W J, Thomas K G F, Laurance H E, Nadel L, 1998 "Place learning in virtual space II: Topographical relations as one dimension of stimulus control" *Learning and Motivation* **29** 288 – 308

Mallot H A, Gillner S, 1997 "Psychophysical support for a view-based strategy in navigation" *Investigative Ophthalmology & Visual Science* **38**(4) S4683

Morris R G M, 1981 "Spatial localization does not require the presence of local cues" *Learning and Motivation* **12** 239 – 260

O'Keefe J, 1991 "The hippocampal cognitive map and navigational strategies", in *Brain and Space* Ed. J Paillard (Oxford: Oxford University Press) pp 273 – 295

O'Keefe J, Nadel L, 1978 *The Hippocampus as a Cognitive Map* (Oxford: Clarendon Press)

Penna M A, Wu J, 1993 "Models for map building and navigation" *IEEE Transactions on Systems, Man, and Cybernetics* **23** 1276 – 1301

Péruch P, Gaunet F, 1998 "Virtual environments as a promising tool for investigating human spatial cognition" *Cahiers de Psychologie Cognitive* **17** 881 – 899

Poucet B, 1993 "Spatial cognitive maps in animals: New hypotheses on their structure and neural mechanisms" *Psychological Review* **100** 163 – 182

Prescott T, 1996 "Spatial representation for navigation in animals" *Adaptive Behavior* **4** 85 – 123

Rolls E T, Treves A, Robertson R G, Georges-François P, Panzeri S, 1998 "Information about spatial view in an ensemble of primate hippocampal cells" *Journal of Neurophysiology* **79** 1797 – 1813

Schölkopf B, Mallot H A, 1995 "View-based cognitive mapping and path planning" *Adaptive Behavior* **3** 311 – 348

Simons D J, Levin D T, 1997 "Change blindness" *Trends in Cognitive Sciences* **1** 261 – 267

Steck S D, Mallot H A, 2000 "The role of global and local landmarks in virtual environment navigation" *Presence: Teleoperators and Virtual Environments* **9** 69 – 83

Trullier O, Wiener S I, Berthoz A, Meyer J-A, 1997 "Biologically based artificial navigation systems: Review and prospects" *Progress in Neurobiology* **51** 483 – 544

Veen H A H C van, Distler H K, Braun S J, Bülthoff H H, 1998 "Navigating through a virtual city: Using virtual reality technology to study human action and perception" *Future Generation Computer Systems* **14** 231 – 242

Zipser D, 1985 "A computational model of hippocampal place fields" *Behavioral Neuroscience* **99** 1006 – 1018