Spatial Memory for Highly Familiar Environments

Julia Frankenstein (julia.frankenstein@tuebingen.mpg.de)
Tobias Meilinger (tobias.meilinger@tuebingen.mpg.de)
Betty J. Mohler (betty.mohler@tuebingen.mpg.de)
Heinrich H. Bülthoff (heinrich.buelthoff@tuebingen.mpg.de)
Max-Planck-Institute for Biological Cybernetics
Spemannstr. 38, 72076 Tübingen, Germany

Abstract

In this experiment we examined orientation dependency in human memory for a highly familiar environmental space. Twenty-seven inhabitants living for at least two years in Tübingen saw a photorealistic virtual model of the city center (Virtual Tübingen) through a head-mounted display. They were teleported to five different initial locations in Virtual Tübingen and asked to point towards well-known target locations. This procedure was repeated in twelve different body-orientations for each of the initial locations. Participants pointed more accurately when oriented northwards regardless of the initial location. We also found a small effect of local orientation. The more participants were aligned with the street leading to the target location the better was their pointing performance. Even though the strong alignment effect with a global orientation is predicted by reference direction theory, this theory does not predict that this global orientation is, first, common for almost all participants, and second, that this orientation is north. We discuss our results with respect to well-known theories of spatial memory and speculate that the bias we find for north orientation is due to participants relying on memory of a city map of Tübingen for their pointing response.

Keywords: spatial memory; reference frame; environmental space; reference direction; view dependent; orientation independent; alignment; map

Introduction

In a familiar environment our spatial memory is needed for us to perform daily tasks. We must remember where our work is located, the route to travel there from our home, and we also need to be able to calculate a detour on occasions when our route is obstructed. A lot of spatial processes likely require a mental representation of our environment. The question addressed in this paper is how highly familiar environments are represented in memory.

Theories of Spatial Memory

There are many theoretical positions concerning the organization of spatial memory (e.g., Burgess, 2006; Gallistel, 1990; O'Keefe & Nadel, 1978; Rump & McNamara, 2007; Wang & Spelke, 2002). Most theoretical positions can be categorized with regard to their prediction of whether humans store their environment orientation dependent with respect to one or more reference directions, orientation dependent with respect to experienced views, and/or orientation independent.

Reference Direction Theory. Reference direction theory states that humans store their spatial knowledge of the environment with respect to one or more reference directions. This theoretical position is mainly supported by McNamara and colleagues (e.g., Kelly, McNamara, Bodenheimer, Carr & Rieser, 2008; Mou, Xiao & McNamara, 2008; Shelton & McNamara, 2001; Rump & McNamara, 2007). The theory states that when learning a new environment, its spatial structure is stored in the specific orientation of a reference direction, whose orientation is determined by either the initial exposure to this environment (e.g., the first view of a room), or by its most salient orientation (intrinsic axis, e.g., parallel to the longer walls of a rectangular room). Initially reference direction theory was only tested in vista spaces. Vista spaces are spaces which could be explored from one point of view, e.g., one single room (see Montello 1993). Spaces such as our city of residence are considered environmental spaces. This kind of space could not be explored from one single point of view, by definition it contains at least two vista spaces which need to be integrated. McNamara, Slucenski and Rump (2008) extended the reference direction theory for environmental spaces, proposing hierarchical reference systems at different scales. Higher-order reference systems (e.g., for a city district) define the spatial relations between lower-order reference systems (e.g., for single streets). By learning an environmental space, humans encode multiple local reference systems with local reference directions. These local reference systems become part of a higher-order reference system by aligning their local reference directions to a single reference direction common for the whole environment. This global reference direction likely differs between individuals, i.e., there is no a priori reason to assume that all individuals should necessarily come up with the same global reference direction. According to this theoretical approach, humans should perform spatial tasks within a highly familiar environment best when they are aligned with the reference direction they use to store the whole environmental space.

View Dependent Memory. Theories proposing a view dependent memory assume that all parts of the environment are stored in the local orientation in which they were explored (e.g., Cartwright & Collett, 1983; Christou & Bülthoff, 1999; Gillner, Weiß & Mallot, 2008; Simons & Wang, 1998; Trullier, Wiener, Berthoz & Meyer, 1997;

Wang & Spelke, 2002). A recent extension of this theoretical approach, the *network of reference frames theory* (Meilinger, 2008; see also Meilinger, Riecke & Bülthoff, submitted) assumes that experienced views of the environment are interpreted as separate local reference frames (i.e., coordinate systems). The environment is represented in a network consisting of these reference frames (each corresponding to a single vista space) and the metric interrelations between these frames (i.e., the translation and the rotation necessary to get from one reference frame to the next one). When humans are required to perform a survey task such as pointing, it is suggested that distant locations are imagined from the perspective of the current location. These reference frames and the stored metric relations between them are integrated within one reference frame in working memory. So contrary to the reference direction theory, which assumes a single *global* reference direction common for the whole environment, this theoretical position proposes best performance when persons are aligned with the *local* orientation of the reference frame of their current location. In a city environment this most often means the alignment with a street orientation as a street is most often experienced in this view. More specifically, the orientation of the street leading to the target of pointing should be the reference standard, because the reference frames on the route to the target location have to be integrated in order to solve a survey task. Participants should thus perform better when aligned with the street leading to the target, than when misaligned.

Orientation Independent Memory. Some authors have proposed that spatial memory is orientation independent (e.g., Burgess, 2006; Byrne, Becker & Burgess, 2007; Gallistel, 1990; Holmes & Sholl, 2005; O'Keefe & Nadel, 1978; Sholl, 2001). One very detailed model of an orientation independent memory was proposed by Sholl and colleagues (e.g., Easton & Sholl, 1995; Holmes & Sholl, 2005; Sholl, 2001). In their theory (as is also the case in most other orientation independent positions), spatial memory is based on at least two interconnected subsystems: a perspective-free allocentric organization of environmental knowledge (object-to-object-system) and an additional egocentric reference system representing space in self-to-object relations. Humans must therefore record and update their positions in relation to the environment, while the positions of the objects in the environment are defined and updated by the relations to other objects, not in relation to a reference direction. For this process a high familiarity with the environment is required. If spatial memory is orientation independent, performance should not vary due to a person's orientation in the environment.

Limitations of Experiments and Results about Spatial Memory

Even though the three theoretical positions described were tested and supported in various experiments (e.g., Christou & Bülthoff, 1999; Easton & Sholl, 1995; Gillner et al., 2008; Holmes & Sholl, 2005; Kelly et al., 2008; Mou et al., 2008), most of the paradigms used did not involve highly familiar environments. In most experiments participants learned the environment specifically for the experiment (an exception is Holmes & Sholl, 2005). This means that the spatial memory tested was newly acquired and not acquired in daily life. Therefore, the results obtained do not necessarily generalize to knowledge of highly familiar environments. In addition, there are at least three more points to mention. First, most experiments were conducted in setups based on vista spaces, for these all three theoretical positions were supported by different experimental results (e.g., Gillner et al., 2008; Kelly et al., 2008; Mou et al., 2008; Shelton & McNamara, 2001). Only orientation independent and view dependent theories have been investigated in environmental spaces (e.g., Christou & Bülthoff, 1999; Holmes & Sholl, 2005). Second, due to experimental control, spatial performance mainly was measured in artificial settings of low complexity. For example, participants learned an array of objects and were tested afterwards (e.g., Shelton & McNamara, 2001; Simons & Wang, 1998). Again, it is an open question whether results obtained also could be generalized to rich and complex environments. Last, no study mentioned so far has directly compared all three theoretical positions within one experimental setting. One study did so in a simple virtual labyrinth (Meilinger, Riecke & Bülthoff, 2007; submitted). Their results indicate that participants encode each corridor of the labyrinth in the orientation it was experienced, rather than relying on a reference direction common for all locations of the labyrinth. However, as this environment was also newly learned during the experiment, familiarity might not have been sufficient to form a global reference direction or an orientation independent memory. In order to learn more about spatial memory for highly familiar environments, we conducted a study which compared predictions from all three theories within one experiment and which examined spatial memory of a highly familiar, complex, and realistic environmental space – namely the memory of one's place of residence.

Methods

Participants wearing a head-mounted display (HMD) were placed in five familiar locations (initial locations) in a virtual model of their hometown (see Figure 1). They were asked to point at different familiar target locations (e.g. the main train station) which were not visible from their location.

Participants

Twelve female and fifteen male participants, aged 18 to 50 years (M = 28.9; SD = 7.8) conducted the experiment. They were recruited via a participant database and by personal contacts and were paid for their participation. All participants were naïve about the theories being investigated in the experiment and had lived for at least two years in Tübingen (M = 6.8; SD = 5.4).

Figure 1: A snapshot of Virtual Tübingen.

Apparatus and Materials

For our experimental setup we used Virtual Tübingen, a highly realistic virtual model of Tübingen, Germany (see Figure 1; http://virtual.tuebingen.mpg.de; Meilinger et al., 2007). Participants saw the model through the HMD as if they were standing (eye-height approximately 1.7 m). In order to keep viewing depth constant in all directions (i.e., when facing a wall vs. looking down a street) we used simulated fog (see Figure 2). The experiment was programmed in Virtools® 4.0 (© Dassault Systemes). We tracked the position and orientation of the participant's head by using an optical tracking system including five reflective markers on the HMD (see Figure 3) and four high-speed motion capture cameras (Vicon® MX 13) which ran with a frame rate of 120 Hz. The participants' head coordinates were transmitted to a computer (Dell Inspiron XPS Gen 2) which rendered an egocentric view of the virtual environment in real-time by using an NVIDIA GO 6800 Ultra graphics card with 256 MB RAM. We presented the stimuli to our participants using a Kaiser SR80 HMD which has a field of view of 53° (vertical) x 63° (horizontal), a resolution of 1280×1024 pixels for each eye and a weight of 0.79 kg (see Figure 3). A fixed interpupillary distance of 8 cm was used for rendering the two views for each eye. We adjusted the fit of the HMD, including the screen placement, for each participant.

Figure 2: Snapshot from the model used in the experiment. The fog ensured comparable viewing distance for all orientations.

The overall setup provided important depth cues such as stereo vision and motion parallax. For measuring participants' pointing performance we used a custom-made pointing joystick (see Figure 3). This joystick provides the ability to determine when people initiated pointing and where they are pointing at in absolute space. The resolution of the joystick is approximately 2 degrees.

Procedure

Our participants found themselves facing a familiar initial location in a specific orientation, which was varied in twelve steps in multiples of 30° (see Figure 3). First, they were asked to self-localize and press a button on the joystick when they felt confident that they knew their position and orientation. Then participants pointed into the virtual direction of three different target locations, whose written names appeared one after the other on the HMD-screen. After pointing the pointing stick had to be held upright again before displaying the next target. Participants self-initiated a trial by pressing a button. Between trials they were allowed to take breaks as much and as long as they wanted. Participants were allowed to rotate their head for self-localization. During pointing they were asked to only look straight ahead (and face the initial orientation), the HMD screen turned black after head rotations larger than 10 degrees. Participants faced all initial locations once in all orientations in random order. No target was pointed to twice in one trial and all targets were pointed to equally often. After finishing all pointing trials, participants were asked to draw the routes they would take from the initial locations to reach the target locations in a city map of Tübingen.

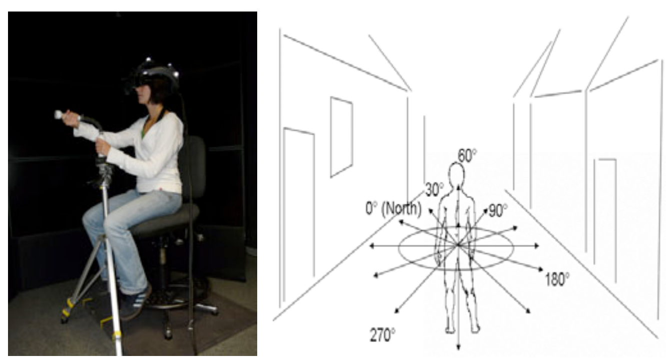

Figure 3: A participant pointing with the pointing joystick (left side). At each initial location participants were tested in each of twelve orientations (right side).

Participants were given written instructions and were also instructed orally. We ensured that they knew the names of initial and target locations by testing them on snapshot images before they participated in the experiment. To gain familiarity with the setup, the joystick and the experimental procedure, participants conducted training trials in a location in virtual Tübingen which was not used as an initial or target location in the experiment. Then for the actual experiment, we recorded the time to self-localize, pointing time and computed the absolute pointing error. The 60 trials (five initial locations in twelve orientations) and three target locations per trial therefore resulted in 180 datasets per participant. For the statistical analysis, values deviating more than three standard deviations from the overall mean were replaced by the most extreme value inside this interval.

Results

Every participants' pointing performance was better than the chance level of 90° (28 t-tests, all $t(179) > 3.86$; $p < .001$). All participants were, therefore, included in the analysis. Analyzing the data for the predictions of the reference direction theory, we found participants' pointing accuracy differing as a function of their global orientation (i.e., alignment with north, east, etc.; $F(4.7, 122.4) = 31.23$, $p < .001$, partial $\eta^2 = .55$). Performance was best when our participants faced north (0° in Figure 4). As the participants might differ in their individual reference direction, we looked at their individual data. 24 of 27 participants were better in facing north than the mean of the other orientations (24 t-tests all $t(1, 179) > 2.39$, $p < .019$, $d > .65$).

Neither the time for self-localization ($F(6.4, 166.1) = 1.70$, $p = .120$, partial $\eta^2 = .06$), nor the time for pointing ($F(3.9, 101.8) = .52$, $p = .715$, partial $\eta^2 = .02$) differed as a function of global orientation, so this result could not be explained by a speed accuracy trade-off.

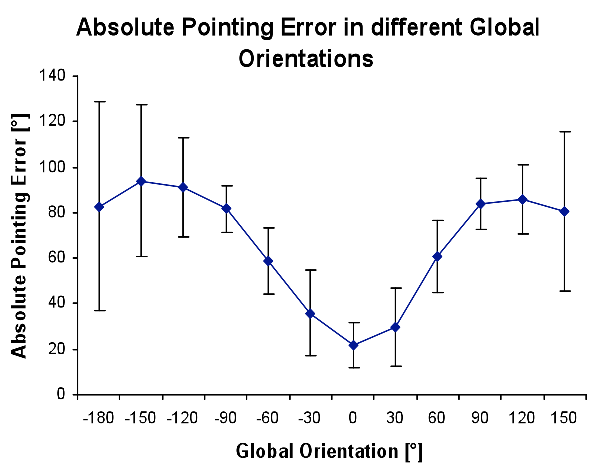

Figure 4: Average pointing error as a function of global orientation. 0° corresponds to facing north, 90° to facing east, -180° to facing south, and -120° to facing west. Error bars represent +- one standard deviation.

We also analyzed the individual routes our participants would take to reach the target locations, and calculated orientation performance relative to the first street in their chosen route. Routes were taken from maps participants drew after the experiment. Pointing accuracy differed as a function of the orientation relative to the street leading to the target location ($F(6.3, 132.5) = 2.37$, $p = .031$, partial $\eta^2 = .101$, see Figure 5).

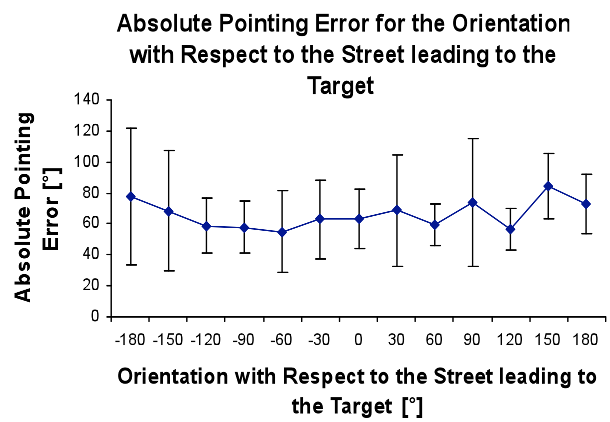

Figure 5: Mean of absolute pointing error across all participants with respect to their orientation to the street leading to the target location. In 0° they were aligned with the street and were looking in the direction they would start their route towards the target location.

Although being aligned with the street leading to the target location did not lead to best performance as predicted by view dependent theories, we did find a significant quadratic trend ($F(1, 21) = 6.45$, $p = .019$, partial $\eta^2 = .24$) indicating that the further participants orientation deviated from this street, the worse performance was. Pointing time did not differ relative to the street leading to the target ($F(2.7, 56.9) = 1.02$, $p = .386$, partial $\eta^2 = .05$).

We did not find significant differences in the time for self-localization depending on the orientation relative to the next street ($F(2.4, 63.4) = .44$, $p = .688$, partial $\eta^2 = .02$). Please note that for self-localization no pointing goal was available and therefore the orientation to the next street instead of orientation relative to the street leading to the target location was calculated.

We did not find a significant difference between males and females in the time they needed to self-localize $t(25) = 1.19$; $p = .246$) or their pointing performance, neither for the pointing error ($t(25) = 1.13$; $p = .269$) nor for reaction time for pointing ($t(25) = .75$; $p = .460$).

Discussion

Participants in our experiment pointed most accurately when they were aligned with topographical north. This was found in the average across participants as well as in the individual data of 24 out of 27 participants. We also found a small effect of local orientation on pointing performance. Pointing performance improved as the participants were aligned with the street leading to the target location.

In our experiment we see a relatively large pointing error on average for the participants. Limitations of the field of view in the HMD-setup could have an effect on task performance (Arthur, 2000) and using special equipment and virtual reality could have lead to poorer task performance, although the patterns of the results seem to be comparable to data gained from natural setups (Ruddle, Payne & Jones, 1997; Sellen, 1998). Since participants were tested within a virtual environment but acquired their knowledge in the real world their poor task performance may have been a factor of transfer from the real to the virtual world.

So is human spatial memory orientation dependent with respect to a reference direction? The reference direction theory (e.g., Kelly et al., 2008; Mou et al., 2008; Shelton & McNamara, 2001; Rump & McNamara, 2007) states that humans encode locations in direction-based spatial reference systems. For highly familiar spaces, as in the present study, humans should have established a global reference direction common for the whole environment (McNamara et al., 2008). The strong effect of global orientation on pointing performance can be seen as evidence for reference direction theory. However, the theory does not provide an explanation for why almost all participants showed the same reference direction. The resulting reference direction for the whole environmental space can be expected to differ due to participants' individual experiences, even more as the structure of Tübingen and the initial locations contain several axes, none of these compelling for use as a global axes. Nor does the theory provide an explanation for why this orientation is north and not east or west, unless especially north would be a very salient orientation in Tübingen or at the initial locations. However, there is no prominent north axis to be found in Tübingen, and the streets within Tübingen do not follow a north-south-east-west grid. The initial locations did not contain more north-south axes than orientations in other directions either. Finally, there were no global landmarks - neither north nor in any other direction - to be seen from the initial locations during the pointing task. Therefore, it does not seem plausible that the observed north orientation originated from the specific structure of Tübingen. So the origin of the observed bias for north in the pointing performance of our participants could not be explained completely by the reference direction theory.

How could our data be interpreted with respect to the view-dependent theory? This class of theories predicts that participants encode their environment not within a global reference frame common for the whole environment, but in the local orientation which the environment was explored (e.g., Cartwright & Collett, 1983; Christou & Bülthoff, 1999; Gillner et al., 2008; Simons & Wang, 1998; Wang & Spelke, 2002). Participants' pointing performance should therefore be better when they are aligned with the local orientation of a street. Best pointing performance is predicted, when the participant is aligned with the street leading to the target location, because then it should be easiest to integrate the sequence of reference frames on the way to the target and so the participant should be able to define the position of the target most accurately. (Meilinger, 2008). The observed alignment effects of the current study do not provide much support for the view dependent theory, the effect we found was rather small and there may be an alternative explanation. For example, pointing to the front has been shown to result in better performance than pointing backwards (Franklin, Henkel & Zangas, 1995). In our experiment the pointing error may have decreased when participants were looking down the street leading to the target location due to the fact that the target location was more often in front of our participants in this case.

The effect of orientation in conducting the pointing task contradicts the theory of an orientation independent memory (e.g., Burgess, 2006; Byrne, Becker & Burgess, 2007; Easton & Sholl, 1995; Gallistel, 1990; Holmes & Sholl, 2005; O'Keefe & Nadel, 1978; Sholl, 2001). Our participants should, since they were living in Tübingen for at least two years, be familiar enough to build up an orientation independent memory.

In conclusion, our results cannot easily be explained by the theories mentioned proposing a view dependent or orientation independent memory. Although the results support the reference direction theory, this theory does not provide an explanation of why most participants performed best when facing north.

We propose that this puzzling pattern is resolved when assuming that participants encoded a city map of Tübingen and used their memory of this map for pointing. City maps are most-often printed with north as up, and they provide all locations within one reference frame. Our results show an alignment effect with topographical north, and the performance curve with slight improvement at 180° is common for using displays in different orientations (Wickens, Vincow & Yeh, 2005).

If in fact true, this interpretation indicates two things. First, the memory of maps encountered may dominate even years of direct experience of an environment. The reason for this may lie in task requirements. For pointing the initial location and the pointing target have to be represented within on single reference frame. Multiple experienced views and translations between them may have to be combined to finally come up with a single reference frame. This might be more complicated and error prone, than using the memory of a city map, which already presents all locations within one single reference frame. Pointing directions are derived from the map rather easily although they have to be transformed into the egocentric perspective from which the pointing task is conducted (Levine, Jankovic & Palij, 1982).

There may be a second issue implied by the interpretation of participants using survey knowledge acquired from a city map used for pointing. In daily life navigators may combine knowledge acquired from multiple sources such as maps and direct experience during navigation to solve spatial tasks (cf. Tversky, 1993). The pointing task in our experiment could not be solved based on map knowledge only, since participants had to determine their location and orientation from visual input of their surrounding environment. The exact nature of this combination of multiple sources and strategies for solving spatial tasks is subject to future research. One could imagine a simple linkage of map-locations to the memory of the corresponding location in the real world. This linkage may be mediated by verbal labels (cf. Meilinger, 2008). However, it is possible as well that map and navigation memory are fused into one representation, or that the map memory serves as a hierarchical top-node which relates to the hierarchical sublevels based on navigation experiences.

Future experiments will have to show which of these speculations best explain our navigation behavior.

Acknowledgements

The authors thank Michael Weyel and Stephan Streuber for support in programming, Hans-Günther Nusseck, Harald Teufel and Benjamin Turski for the virtual reality environment.

References

Burgess, N. (2006). Spatial memory: how egocentric and allocentric combine. *Trends in Cognitive Sciences, 10,* 551-557.

Byrne, P., Becker. S. & Burgess, N. (2007). Remembering the Past and Imagining the Future: A Neural Model of Spatial Memory and Imagery. *Psychological Review, 114,* 340-375.

Carthwright, B.A. & Collett, T.S. (1983). Landmark Learning in Bees. *Journal of Comparative Physiology, 151,* 521-543.

Christou, C. & Bülthoff, H.H. (1999). View dependence in scene recognition after active learning. *Memory & Cognition ,27,* 996-1007.

Easton, R.D., & Sholl, M.J. (1995). Object-array structure, frames of reference, and retrieval of spatial knowledge. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21,* 483-500.

Franklin, N., Henkel, L.A. & Zangas, T. (1995). Parsing surrounding space into regions. *Memory and Cognition, 2*3, 397-407.

Gallistel, C.R. (1990). *The Organization of Learning.* Cambridge, MA: MIT Press.

Gillner, S., Weiß, A.M. & Mallot, H.A. (2008) Visual homing in the absence of feature-based landmark information. *Cognition, 9,* 105-122.

Holmes, M.C. & Sholl, M.J. (2005). Allocentric coding of object-to-object relations in overlearned and novel environments. *Journal of Experimental Psychology: Learning, Memory and Cognition, 31,* 1069-1078.

Kelly, J.W., McNamara, T.P., Bodenheimer, B., Carr, T.H. & Rieser, J.J. (2008). The shape of human navigation: How environmental geometry is used in maintenance of spatial orientation. *Cognition, 109,* 281-286.

Levine, M., Jankovic, I.N., & Palij, M. (1982). Principles of spatial problem solving. *Journal of Experimental Psychology General, 111,* 157-175.

McNamara, T.P., Slucenski, J., & Rump, B. (2008). Human Spatial Memory and Navigation. In H.L. Roedinger, III (Ed.), *Cognitive Psychology of Memory. Vol. [2] of Learning and Memory: A comprehensive Reverence, 4 vols. (J.Byrne Editor)*. Oxford: Elsevier.

Meilinger, T. (2008). The Network of Reference Frames Theory: A Synthesis of Graphs and Cognitive Maps. In C. Freksa, N. S. Newcombe, P. Gärdenfors, S. Wölfl (Eds.), *Spatial Cognition VI*. Berlin: Springer

Meilinger, T., Riecke, B.E. & Bülthoff, H.H. (submitted). Recently learned environmental spaces are represented as interconnected vista spaces. *Cognition.*

Meilinger, T., Riecke, B.E. & Bülthoff, H.H. (2007). Orientation Specificity in Long-Term-Memory for Environmental Spaces. *Proceedings of the 29th Annual Conference of the Cognitive Science Society.*

Montello, D. R. (1993). Scale and multiple psychologies of space. In A. U. Frank & I. Campari (Eds.), *Spatial information theory: A theoretical basis for GIS*. Berlin: Springer.

Mou,W., Xiao, C. & McNamara, T.P. (2008). Reference directions and reference objects in spatial memory of a briefly viewed layout. *Cognition, 108,* 136-154

O'Keefe, J., & Nadel, L. (1978). *The hippocampus as a cognitive map.* Oxford: Clarendon Press.

Ruddle, R.A., Payne, S.J. & Jones, D.M. (1997). Navigating buildings in "desk-top" virtual environments: experimental investigations using extended navigational experience. *Journal of Experimental Psychology: Applied, 3(2),* 143-159.

Rump, B. & McNamara, T.P. (2007). Updating in Models of Spatial Memory. In T. Barkowsky, M. Knauff, G. Ligozat, D.R. Montello (Eds.), *Spatial cognition V*. Berlin: Springer.

Sellen, K. (1998). *Schätzen von Richtungen in realen und virtuellen Umgebungen.* Diploma thesis, Tübingen University, Faculty of Biology.

Shelton, A.L., & McNamara, T.P. (2001). Systems of spatial reference in human memory. *Cognitive Psychology, 43,* 274–310.

Sholl, M.J. (2001). The Role of a Self-Reference System in Spatial Navigation. In D.R. Montello (Ed.), *COSIT 2001* (pp. 217−232). Berlin: Springer.

Simons, D.J., & Wang, R.F. (1998). Perceiving real-world viewpoint changes. *Psychological Science, 9,* 315-320.

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.

Tversky, B. (1993). Cognitive maps, cognitive collages, and spatial mental models. In A. U. Frank & I. Campari (Eds.), *Spatial information theory: A theoretical basis for GIS* (pp. 14-24). Berlin: Springer.

Wang, F.R., & Spelke, E. S. (2002). Human spatial representation: insights form animals. *Trends in Cognitive Sciences, 6,* 376-382.

Wickens, C.D., Vincow, M. & Yeh, M. (2005). Design applications of visual spatial thinking: The importance of frame of reference. In P. Shah & A. Miyake (Eds.), *The Cambridge Handbook of Visuospatial Thinking*. Cambridge: Cambridge University Press.