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Brief article

Learning to navigate: Experience versus maps

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ABSTRACT

People use “route knowledge” to navigate to targets along familiar routes and “survey knowledge” to determine (by pointing, for example) a target’s metric location. We show that both root in separate memories of the same environment: participants navigating through their home city relied on representations and reference frames different from those they used when doing a matched survey task. Tübingen residents recalled their way along a familiar route to a distant target while located in a photorealistic virtual 3D model of Tübingen, indicating their route decisions on a keyboard. Participants had previously done a survey task (pointing) using the same start points and targets. Errors and response latencies observed in route recall were completely unrelated to errors and latencies in pointing. This suggests participants employed different and independent representations for each task. Further, participants made fewer routing errors when asked to respond from a horizontal walking perspective rather than a constant aerial perspective. This suggests that instead of the single reference, north-up frame (similar to a conventional map) they used in the survey task, participants employed different, and most probably multiple, reference frames learned from “on the ground” navigating experience. The implication is that, within their everyday environment, people use map or navigation-based knowledge according to which best suits the task.

1. Introduction

People constantly find their way from one place to another – bedroom to bathroom; home to work – along familiar routes. Their wayfinding is guided at each decision point along the way by their underlying route knowledge (Golledge, 1999; Ishikawa & Montello, 2006; Mallot & Basten, 2009; Siegel & White, 1975; Thorndyke & Hayes-Roth, 1982; Trullier, Wiener, Berthoz, & Meyer, 1997; Wiener, Böchner, & Hölscher, 2009). By contrast, when people estimate distances and directions between mutually non-visible locations without necessarily knowing the connecting route they are informed by “survey knowledge”. Route and survey knowledge of an area seem not to be tied together in a developmental sequence as often as suggested (Piaget, Inhelder, & Szeminska, 1960; Siegel & White, 1975); some navigators develop survey knowledge immediately, some over time, others never (Appleyard, 1970; Holding & Holding, 1989; Hölscher, Meilinger, Vrachliotis, Brösamle, & Knauff, 2006; Ishikawa & Montello, 2006; Moeser, 1988; Montello & Herbert, 1993). However, it remains unknown whether route and survey knowledge depend on different strategies operating on one representation (e.g., a mental map), or on different

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representations, and whether they use the same reference frame.[1]

To shed light on these questions we asked Tübingen residents to perform route and survey tasks with identical start and target locations, examining participant's knowledge of their home city acquired over years. Survey data were collected 1 week earlier as part of another study (Frankenstein, Mohler, Bülthoff, & Meilinger, 2012) and analyzed in conjunction with the route data. We hypothesized that if participants used a single representation for the two types of tasks their performance in both should be correlated. For example, a wrong turn on a route to a target location would correspond to a direction error when pointing to that location. Thus, more route errors should correspond to larger pointing errors. If they used different representations, however, no such correlations should be found. Related studies have not investigated this, having compared aggregated measures between participants, but not within participants' own performance (Appleyard, 1970; Hölscher, Büchner, Meilinger, & Strube, 2009; Ishikawa & Montello, 2006; Moeser, 1988; Montello & Herbert, 1993; Thorndyke & Hayes-Roth, 1982).

If people use different representations for route and survey tasks they might nevertheless use the same reference frames. For example, a photograph and a description of a scene are different representations, but they may use the same reference point and orientation. For survey knowledge, single reference frame representations have been described for learning simple environments from video or descriptions (Shelton & McNamara, 2004; Taylor & Tversky, 1992; Wilson, Tlauka, & Wildbur, 1999). In the population tested here, survey knowledge of one's city of residency is represented in a single, north-oriented reference frame likely acquired from maps (Frankenstein et al., 2012). When experiencing a complex environment by walking only, multiple local reference frames may be more important (Meilinger, Riecke, & Bülthoff, in press).

The reference frames underlying route knowledge have not been examined as much as those underlying survey knowledge. Theory states that route knowledge relies on multiple interconnected units (Mallot & Basten, 2009; Meilinger, 2008; Poucet, 1993; Trullier et al., 1997). These units (e.g., snapshots, local environments) serve to identify a location while their connections inform the navigator where to go next (e.g., a direction or street) or trigger a learned behavior. Thus route knowledge relies on multiple local reference frames. This has not, however, been demonstrated empirically until now.

To see whether route and survey knowledge reference frames differ, we varied the imagined perspective in which the route knowledge was recalled. Participants indicated their routing decisions (e.g., left, straight, right, etc.) both from an imagined horizontal, *walking* perspective and from a single imagined *aerial*, bird's eye or map perspective (Fig. 1). Spatial information is stored in a certain reference frame orientation, and accessing it from a different orientation usually yields inference costs such as errors or delays (McNamara, Sluzenski, & Rump, 2008). Otherwise it is classified as orientation-free. Performance measures may therefore reveal underlying reference frames. If the person is using a single reference frame it need be aligned once only with the aerial perspective during recall, but multiple times (i.e., after each turn) in the walking perspective (cf., paper map rotation during route navigation). Thus, we expect the person to perform better when doing the task from the aerial perspective. If participants use multiple local reference frames however, they should do better in the walking perspective (Meilinger, Franz, & Bülthoff, 2012) as the multiple frames would be identical with it and thus have no alignment costs.[2]

2. Methods

2.1. Participants

Twenty-three naïve participants (ten female), aged 18–50 years ($M = 28.5$; $SD = 7.7$) recruited from a subject database participated in exchange for monetary compensation after giving informed consent. They lived for at least 2 years in Tübingen ($M = 7.7$; $SD = 5.9$). All participants had performed the parallelized pointing task 1 week earlier (Frankenstein et al., 2012) and we reanalyzed these data. Two additional participants could not participate and additional two did not succeed in performing the task. The experiment was approved by the local ethics committee.

2.2. Materials

We used Virtual Tübingen, a highly realistic virtual model of Tübingen, Germany (see Fig. 2; http://virtual.tuebingen.mpg.de). Participants saw the model in horizontal perspective through a Kaiser SR80 head mounted display (HMD) while sitting on a swivel chair. Fog occluded adjacent intersections. We tracked head movements and rendered a stereo view of the virtual environment with a field of view of 63° (horizontal) × 53° (vertical) in real time. For further technical details see Frankenstein et al. (2012). We adjusted HMD fit and screen placement individually for every participant. The overall setup provided important depth cues such as stereo vision and motion parallax. Participants typed in route sequences with the arrow keys of a custom keyboard resting on their legs (see Fig. 2) and pointed in the identical setup using a custom made joystick.

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[1] A reference frames is defined here as a reference location and orientation relative to which locations (and orientations) are represented.

[2] In walking vs. aerial testing, answers were given from a constant global reference frame or from reference frames changing after each turn. This difference was confounded with imagining a horizontal vs. a top down viewpoint. Any differences found might thus originate from answering from a constant vs. variable reference frames or from imagining a horizontal vs. top down viewpoint. To resolve the confound, participants could have been tested always from an imagined horizontal viewpoint, and indicated movement one time in the local street orientation as described and another time in a constant body orientation (e.g., always facing north), just without looking down from above. Unfortunately, this instruction was too complicated to understand. Therefore, we used the instruction confounding viewpoint and reference frame constancy. We address consequences for the interpretation of data in the discussion.

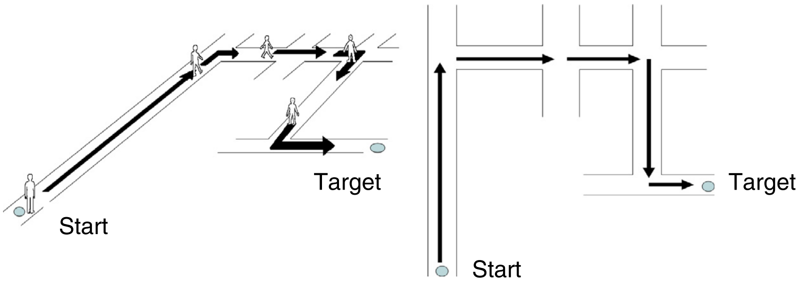

Fig. 1. Schematic drawing of correct sequences of the same route. Left side: walking perspective "right, straight, right, left"; Right side: aerial perspective "right, right, down, right".

Fig. 2. Left side: a snapshot from Virtual Tübingen with fog. Right side: participant equipped with a HMD, sitting on a swivel chair and typing in a route sequence.

2.3. Procedure

In every route and survey trial, participants faced a start location, looked around and confirmed recognition of location and orientation by pressing a button (Fig. 2 left). The written name of the target location (e.g., a tavern, train station, fire hall) appeared on the HMD-screen. Participants were asked to report the route they would take to reach the target location. They turned to face the initial direction of their chosen route, pressed the "up/forward" arrow key on the keyboard, entered the remaining sequence, and finished by pressing "space". Participants were told to enter one decision for each intersection along the route, but to ignore dead-ends. Participants always remained at the starting location in Virtual Tübingen and were not moved through the virtual world, i.e., they faced the same scene as if they were standing at that start location during the whole recall procedure in both perspectives. For recall in walking perspective, they imagined seeing remote intersections, for recall in aerial perspective they imagined watching the scene from above. Participants were not instructed to imagine a map. Participants performed two blocks of 30 trials in walking and aerial perspective with the order of perspectives counterbalanced between participants. Within a block, the order of the four start locations and the order of seven or eight targets per start location were fully randomized for each participant.

In the survey task, participants faced the same starting locations, but remained in a fixed body orientation and used a joystick to point to the target. At each location, they pointed equally often facing all global body orientations (i.e., from 0° to 330° in steps of 30°) in randomized order. Within this variation, each target was pointed to three times and we averaged absolute angular differences.

In both experiments, participants controlled inter-trial intervals themselves, and did not receive any feedback. They had successfully identified start and target locations on snapshots displaying only locally visible landmarks before the experiment. Participants received written and oral instructions.

After the experiment participants were asked to draw the routes entered before into paper maps of Tübingen, one for each start-target pair. For every participant, his/her individual drawn routes were used as the reference relative to which to determine the individual errors in the entered sequences. The absolute number of errors per sequence reflected the added absolute number of deviations from lefts, rights, ups/forwards, and downs along an individual reference route, not an arbitrary standard route.[3] We recorded latencies for initializing the whole sequence. Average key press speed for the remaining sequence (i.e., excluding first key press) showed identical results and is thus not reported. Routes where participants drew a wrong start or target location into the map, or route or survey trials with error or latency data deviating more than three standard deviations from the overall mean were excluded from analysis.

2.4. Statistical analysis

For the same start and target combination, absolute pointing errors and latencies in survey trials were correlated with the absolute number of errors and latencies in route trials. This was done individually for each participant for walking and aerial perspective separately, resulting in eight correlations (see Fig. 1).[4] The distribution of individual correlations was compared to no correlation ($r = 0$) and to a small correlation ($r = .20$) using one-sample t-tests. For evidence in favor of the null-hypothesis of no correlation, we also analyzed the data with one sample Bayesian hypothesis tests as proposed by Rouder, Speckman, Sun, Morey and Iverson, 2009.

For analysis of perspective, we submitted means in error and latency per participant and condition to an ANOVA with the within-participants factor "perspective" and the between-participants factor "order". Adding gender did not reveal any main effects or interactions and is not reported. Participants' performance did not differ with respect to self-localization time.

3. Results

3.1. Correlations between route and survey measures

Route and survey knowledge were uncorrelated: distributions of within-participant correlations did not differ from $r = 0$ neither for horizontally tested route knowledge (Fig. 3 top row; four $t(22)$'s < 0.51; p's > .701), nor for vertically tested route knowledge (bottom row four $t(22)$'s < 1.79; p's > .087). They even were significantly smaller than a small correlation of $r = .20$ (eight $t(22)$'s > 3.3; p's < .003; Bonferroni corrected alpha threshold: .05/8 = .00625).

All but one Bayes factor were larger than 3 supporting the null hypothesis of $r = 0$, which was in average 5.4 time more likely than the alternative of a (positive or negative) correlation. One distribution (survey and route errors from aerial perspective) was indecisive. However, the average correlation was negative and thus even more deviated from a positive correlation between route and survey measures.

3.2. Walking versus aerial perspective

As shown in Fig. 4, participants' route sequences were more accurate in the walking (errors: $M = 7.29$; $SD = 2.16$) than in the aerial perspective ($M = 8.44$; $SD = 1.70$; $F(1,21) = 15.57$, $p = .001$ $\eta_p^2 = .43$). This result was predicted by reliance on multiple local reference frames, but not by relying on a single reference frame as employed in survey knowledge. Latency did not differ between perspectives ($p > .20$). However, participants initialized sequences faster in the second block of testing ($F(1,21) = 7.87$, $p = .011$ $\eta_p^2 = .27$).

The proportions of turns entered was significantly lower than expected by mere guessing among three alternatives in walking perspective (value expected by chance performance = 0.667; observed mean 0.37; $t(22) = 22.3$, $p < .001$) and four alternatives in the aerial perspective (expected value 0.75; observed mean 0.54; $t(22) = 6.67$, $p < .001$). As participants were not guessing, the perspective difference cannot be attributed to the higher number of alternatives in the aerial perspective.

4. Discussion

The question of the relationship between route and survey knowledge was raised by Piaget, Inhelder and Szeminska more than half a century ago, but it has still not been fully answered (Golledge, 1999; Ishikawa & Montello, 2006; Mallot & Basten, 2009; Piaget et al., 1960; Siegel & White, 1975; Thorndyke & Hayes-Roth, 1982; Trullier et al., 1997; Wiener et al., 2009). Present results show that in a highly familiar space – one's city of residence – route and survey measures are uncorrelated even within participants. Rather than being different processes rooted in the same representation, the underlying representations of each appear to be different.

Were the null correlations due to noise from different task requirements or other factors? Such noise would have prevented finding a perspective difference, or support for the null-hypothesis in Bayesian testing. Rather than noise, we think that different underlying representations are more plausible.

The higher accuracy in walking as compared to aerial perspective suggests that route knowledge is *not* represented in the single north-up reference frame probably underlying participants' survey knowledge (Frankenstein et al., 2012). With such a reference frame, the opposite pattern would have been expected: aerial testing would have required fewer alignments and thus resulted in better performance. The perspective difference was predicted theoretically by multiple local reference frames (Mallot &

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[3] Deviations from required straights and turns do not consider errors in route order, for example, typing left-right instead of right-left. Levenshtein or edit distance (Levenshtein, 1966) does so to some extent: it estimates the minimum number of sequence elements to be altered, inserted, or erased in order to obtain the reference sequence from the entered sequence. Usually, different possibilities of alteration exist, so errors are still difficult to attribute to individual intersections. Analyzing our data by Levenshtein distances instead of number of errors, we observed very similar effects. For example, also the perspective effect was significant. We thus conclude that route order errors were not central.

[4] We also carried out a correlation analysis not based on route errors, but on the reconstruction of a target location from the route sequence. For example, the target location was in fact to the front, but a participant's sequence indicated turning left and then walk straight on. The route led to a target location on the left rather to the front. This offset was correlated with pointing error and latency. The obtained results were highly similar to the ones described and are thus not reported.

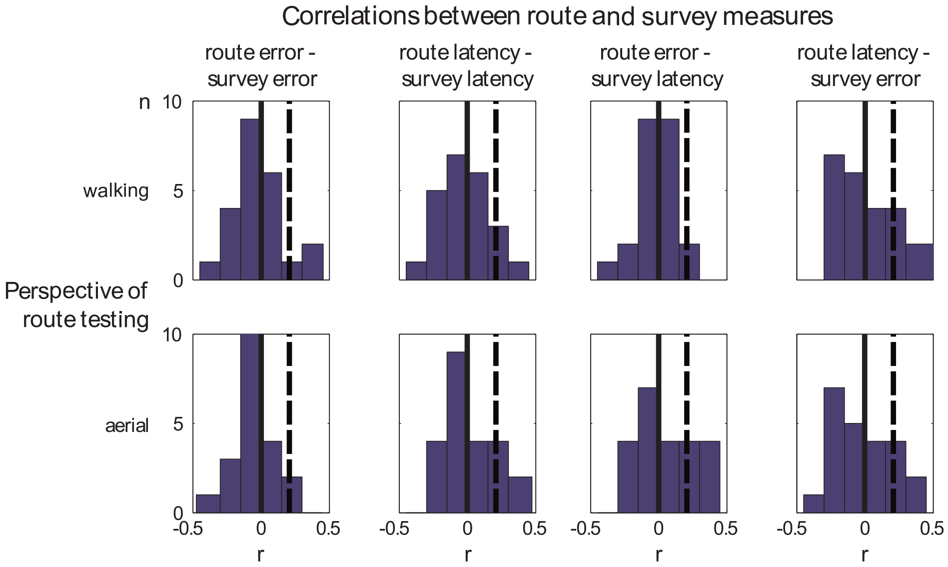
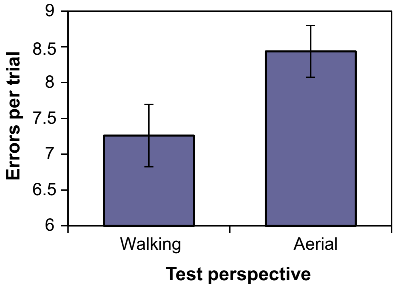


Fig. 3. Frequency of correlation coefficient sizes in correlations of route and survey tasks within participants (i.e., one correlation per participant). All correlation distributions cluster around $r = 0$ (continuous line) and do not significantly differ from it, but are significantly smaller than a correlation of $r = .20$ (dotted line).



	Mean	Std. Error
Walking	7.260214	0.435776
Aerial	8.436641	0.361644

Fig. 4. Route sequence errors in tests from walking and aerial perspective. Means and standard errors are displayed.

Basten, 2009; Meilinger, 2008; Poucet, 1993; Trullier et al., 1997). Consequently, we conclude that route and survey knowledge employ different reference frames.

Are there alternative interpretations for the present data? One is that participants used a horizontal, but otherwise orientation-free representation. This is consistent with the observed perspective difference. No relevant alignment costs occur in orientation-free reference frames, but switching the horizontal representation into the aerial test perspective is costly and would therefore produce the observed results.

Furthermore, participants might have relied on completely orientation-free reference frames and perspective difference might have originated from the test situation: Participants imagined remote route locations while being oriented horizontally both physically (they did not face the floor) and within their virtual surrounding. Was it thus easier to imagine a horizontal viewpoint in the walking perspective than a vertical viewpoint in aerial perspective testing? Such advantages for consistency between current and imagined viewpoints have been reported for imagining viewpoints within the current surrounding, but not – as in our study – for imagining remote locations (Kelly, Avraamides, & Loomis, 2007; cf., Brockmole & Wang, 2003). Even in these two interpretations, route and survey representations rely on different reference frames: (horizontal) orientation-free representations are clearly different from the single, north-up reference frame underlying survey knowledge (Frankenstein et al., 2012).

Although (horizontal) orientation-free route knowledge is a valid interpretation of the perspective difference, we do not think it is very plausible. There is hardly any evidence for orientation-free representations at all (for an overview see McNamara et al., 2008). Even recent results of recalling a central place in Tübingen by city residents indicated clear orientation-dependency (Basten, Meilinger, & Mallot, 2012). Furthermore, orientation-free route knowledge cannot explain route direction priming (Janzen, 2006) or route choice differences for reverse routes (Golledge, 1995; Stern & Leiser, 1988). A graph consisting of multiple local reference frames naturally does so (Meilinger, 2008) and we consider this to be the more plausible interpretation of the data.

Multiple reference frames in route knowledge and a single, north-up reference frame in survey knowledge nicely fit with different learning sources for route and survey knowledge, namely learning from navigation experience versus from maps. By employing maps (i.e., north-up, single reference frame representation) for survey tasks, navigators avoid integrating multiple views experienced during navigation within one reference frame. Route navigation, however, can be based on local reference frames and their interconnections. In doing so, navigators also profit from specific advantages of these information sources: for most tasks, more accurate survey knowledge is acquired from maps whereas more accurate route knowledge is acquired from navigation experience (Lloyd, 1989; Moeser, 1988; Rossano, West, Robertson, Wayne, & Chase, 1999; Taylor, Naylor, & Chechile, 1999; Thorndyke & Hayes-Roth, 1982). Navigators thus seem to select the optimal information source for a task at hand even though they represent the same environment twice.

Different information sources may be used only in situations where maps of the environment are accessible and appropriate. Where they are not, within most buildings or within easy to grasp city-grids, for instance, route and survey knowledge might be interrelated more strongly and may even be based on a single representation.

The comparison standard for computing route errors was a route drawn on paper by the same participant after entering the route sequences. Routes drawn and indicated by sequences might have differed. Severe cases of deviations are unlikely, as trials with start or target locations drawn at wrong locations were not analyzed as were trials with extreme deviations in errors or latencies. Nevertheless, errors in recalling the entered routes during drawing as well as the large pointing errors might have contributed to the null correlation. Concerning the perspective effect, one might argue that estimating errors relative to a route drawn from aerial perspective might give an advantage to aerial route testing. However, consistent with multiple local reference frames, the opposite pattern was observed.

5. Conclusions

People draw on different information for different spatial tasks. They use navigation experience, likely organized in multiple local reference frames, to select familiar routes. By contrast, they use single-reference, north-up information probably acquired from maps to do survey tasks such as pointing.

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References

Appleyard, D. (1970). Styles and methods of structuring a city. *Environment and Behavior, 1*, 131–156.

Basten, K., Meilinger, T., & Mallot, H. A. (2012). Mental travel primes place orientation in spatial recall. In C. Stachniss, K. Schill, & D. H. Uttal (Eds.), *Spatial cognition VIII* (pp. 378–385). Berlin: Springer.

Brockmole, J. R., & Wang, R. F. (2003). Changing perspective within and across environments. *Cognition, 87*, 59–67. http://dx.doi.org/10.1016/S0.

Frankenstein, J., Mohler, B. J., Bülthoff, H. H., & Meilinger, T. (2012). Is the map in our head oriented north? *Psychological Science, 23*(2), 120–125. http://dx.doi.org/10.1177/0956797611429467.

Golledge, R. G. (1995). Path selection and route preference in human navigation: A progress report. *Spatial Information Theory, 988*, 207–222.

Golledge, R. G. (1999). *Wayfinding behavior*. Baltimore: The John Hopkins University Press.

Holding, C. S., & Holding, D. H. (1989). Acquisition of route network knowledge by males and females. *The Journal of General Psychology, 116*, 29–41.

Hölscher, C., Büchner, S. J., Meilinger, T., & Strube, G. (2009). Adaptivity of wayfinding strategies in a multi-building ensemble: The effects of spatial structure, task requirements, and metric information. *Journal of Environmental Psychology, 29*(2), 208–219. http://dx.doi.org/10.1016/j.jenvp.2008.05.010.

Hölscher, C., Meilinger, T., Vrachliotis, G., Brösamle, M., & Knauff, M. (2006). Up the down staircase: Wayfinding strategies in multi-level buildings. *Journal of Environmental Psychology, 26*(4), 284–299. http://dx.doi.org/10.1016/j.jenvp.2006.09.002.

Ishikawa, T., & Montello, D. R. (2006). Spatial knowledge acquisition from direct experience in the environment: Individual differences in the development of metric knowledge and the integration of separately learned places. *Cognitive Psychology, 52*(2), 93–129. http://dx.doi.org/10.1016/j.cogpsych.2005.08.003.

Janzen, G. (2006). Memory for object location and route direction in virtual large-scale space. *Quarterly Journal of Experimental Psychology, 59*(3), 493–508. http://dx.doi.org/10.1080/02724980443000746.

Kelly, J. W., Avraamides, M. N., & Loomis, J. M. (2007). Sensorimotor alignment effects in the learning environment and in novel environments. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33*(6), 1092–1107. http://dx.doi.org/10.1037/0278-7393.33.6.1092.

Levenshtein, V. I. (1966). Binary codes capable of correcting deletions, insertions, and reversals. *Soviet Physics Doklady, 10*, 707–710.

Lloyd, R. (1989). Cognitive maps – Encoding and decoding information. *Annals of the Association of American Geographers, 79*(1), 101–124.

Mallot, H. A., & Basten, K. (2009). Embodied spatial cognition: Biological and artificial systems. *Image and Vision Computing, 27*(11), 1658–1670. http://dx.doi.org/10.1016/j.imavis.2008.09.001.

McNamara, T. P, Sluzenski, J., & Rump, B. (2008). Human spatial memory and navigation. In H. L. Roediger (Ed.), *Cognitive psychology of memory*. In & J. Byrne (Eds.). *Learning and memory: A comprehensive reference* (Vol. 2). Oxford: Elsevier (4 vols).

Meilinger, T., Franz, G., & Bülthoff, H. H. (2012). From isovists via mental representations to behaviour: First steps toward closing the causal chain. *Environment and Planning B-Planning and Design, 39*(1), 48–62. http://dx.doi.org/10.1068/B34048t.

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. (in press). Local and global reference frames for environmental spaces. *The Quarterly Journal of Experimental Psychology* (in press).

Moeser, S. D. (1988). Cognitive mapping in a complex building. *Environment and Behavior, 20*(1), 21–49.

Montello, D. R., & Herbert, L. P. (1993). Integrating knowledge of vertically aligned large-scale spaces. *Environment and Behavior, 25*, 457–484.

Piaget, J., Inhelder, B., & Szeminska, A. (1960). *The child's conception of geometry*. New York: Basic Books.

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

Rossano, M. J., West, S. O., Robertson, T. J., Wayne, M. C., & Chase, R. B. (1999). The acquisition of route and survey knowledge from computer models. *Journal of Environmental Psychology, 19*(2), 101–115.

Rouder, J. N., Speckman, P. L., Sun, D., Morey, R. D., & Iverson, G. (2009). Bayesian t tests for accepting and rejecting the null hypothesis. *Psychonomic Bulletin & Review, 16*(2), 225–237. http://dx.doi.org/10.3758/PBR.16.2.225.

Shelton, A. L., & McNamara, T. P. (2004). Orientation and perspective dependence in route and survey learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 30*(1), 158–170. http://dx.doi.org/10.1037/0278-7393.30.1.158.

Siegel, A. W., & White, S. H. (1975). The development of spatial representations of large-scale environments. In H. Reese (Ed.). *Advances in child development and behavior* (Vol. 10, pp. 10–55). New York: Academic Press.

Stern, E., & Leiser, D. (1988). Levels of spatial knowledge and urban travel modeling. *Geographical Analysis, 20*(2), 140–155.

Taylor, H. A., Naylor, S. J., & Chechile, N. A. (1999). Goal-specific influences on the representation of spatial perspective. *Memory and Cognition, 27*(2), 309–319.

Taylor, H. A., & Tversky, B. (1992). Descriptions and depictions of environments. *Memory and Cognition, 20*, 483–496.

Thorndyke, P. W., & Hayes-Roth, B. (1982). Differences in spatial knowledge acquired from maps and navigation. *Cognitive Psychology, 14*, 560–589.

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.

Wiener, J., Büchner, S., & Hölscher, C. (2009). Taxonomy of human wayfinding tasks: A knowledge-based approach. *Spatial Cognition and Computation, 9*(2), 152–165. http://dx.doi.org/10.1080/13875860902906496.

Wilson, P. N., Tlauka, M., & Wildbur, D. (1999). Orientation specificity occurs in both small- and large-scale imagined routes presented as verbal descriptions. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 25*, 664–679.