Towards a Computational Spatial Knowledge Acquisition Model in Architectural Space

Junchao Lyu[1], Bauke de Vries[2], and Chengyu Sun[1]

[1] Faculty of Architecture, College of Architecture and Urban Planning,
Tongji University, Shanghai, China
jeromelue@gmail.com, ibund@126.com
[2] Faculty of Architecture, Building and Planning Eindhoven University of Technology,
Eindhoven, Netherlands
b.d.vries@tue.nl

Abstract. Existing research which is related to spatial knowledge acquisition often shows a limited scope because of the complexity in the cognition process. Research in spatial representation such as space syntax presumes that vision drives movement. This assumption is only true under certain conditions and makes these models valid only in specific scenarios. Research in human spatial cognition field suggests that the spatial information perceived by the individual is not equal to the visual appearance of the space, a straightforward way to represent this cognition process quantitatively is lacking. Research in wayfinding usually assumes a certain degree of familiarity of the environment for the individual, which ignores the fact that the individual sequentially perceives information during wayfinding and the familiarity of the environment changes during the wayfinding process.

In this paper, a conceptual spatial knowledge acquisition model for architectural space is presented based on the continuous spatial cognition framework. Three types of local architectural cues are concluded to relate common architectural elements to the continuous spatial cognition framework. With all relations in the proposed conceptual model quantitatively described, a computational model can be developed to avoid the aforementioned limitations in spatial representation models, human spatial cognition models and wayfinding models. In this way, our computational model can assist architects evaluate whether their designed space can be well perceived and understood by the users. It can help enhance the way-finding efficiency and boost the operational efficiency of many public buildings.

Keywords: local architectural cues, spatial knowledge, human cognition framework.

1 Limits in Current Research

Existing spatial representation models, human spatial cognition models and wayfinding models, exhibit limitations that follow from the assumptions underlying these models. An overview of these limitations and assumptions is presented in the next sections.

J. Zhang and C. Sun (Eds.): CAAD Futures 2013, CCIS 369, pp. 256–266, 2013.

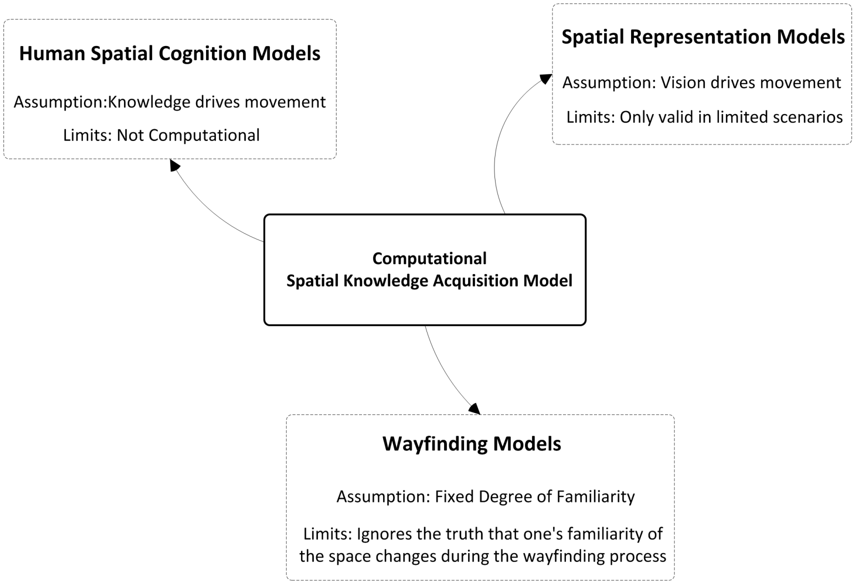

Fig. 1. Overview of assumptions and limitations of existing spatial knowledge acquisition models

1.1 Limitations in Spatial Representation Models

Since the notion of legibility introduced by Lynch [1], researchers have tried to represent the complexity of a floor plan layout quantitatively, namely through a spatial representation [2-6]. Notably, space syntax is the most influential one among them, in which the spatial organization is represented by a set of computational maps such as axial maps, isovist maps, and integration maps [7]. Each map reflects one feature of the spatial organization of the architectural space. Such quantitative representation of the architectural space could be directly used in the design of space by architects and urban designers. However, the assumption that these methods build upon brings limitations to them. The assumption is based on Gibson's notion of optic flow, which indicates that animals' movements are decided by their visions, and they move simply because they want to see more [8]. In other words, vision drives movements. For example, theisovist was first introduced by Benedikt as a tool for modeling human space perception in the context of architectural design [9]. It is the set of all points visible from a given vantage point in space and defines a field of vision from which various pure geometrical properties, such as area and perimeter, can be calculated [10]. Benedikt starts by considering the volume visible from a location and then simplifies this representation by taking a horizontal slice through the isovist polyhedron [11]. However, this 360 degree range of vision calculated from the building plan does not coincide with the actual perception of individuals in the environment. Empirical findings by Werner and Schindler revealed thatthe floor plan layout is quite different from the spatial knowledge which drives individual's wayfinding [6]. Because isovists serve as the basis for many kinds of computational maps such as the axial lines by Hillier and Hanson [12], convex partitions by Peponis [13], and the integration maps by Turner [11]. the assumption of human perception that ‘vision drives movements’ propagates through these spatial representations. These methods are only valid for specific scenarios in which individuals move like animals with no specific targetsand thus are not applicable to many architectural designs.

1.2 Limitations in Human Spatial Cognition Models

Research in human spatial cognition allows for the consideration of how spatial information is retrieved and processed in the human brains. It is well acknowledged that the individual’s spatial perception is built sequentially from the pieces of local information in a large-scale space [6]. Researchers aim to identify how an individual’s spatial knowledge is acquired from space and constructed in the brains, indicated as spatial knowledge acquisition. Up till now, there are two existing human cognition frameworks to help to decipher this process. They are the dominant framework proposed by Siegel and White and the continuous framework proposed by Montello [14, 15]. Both frameworks give guidelines on how local information is acquired and integrated into spatial knowledge. However, because of the complexity of these processes, current research in this field only partially reveals the relations between architectural space and the spatial knowledge acquisition process. For example, Werner and Ben-Yehoshua focused on the impact of the shape of wall corners [6, 16]. Other research revealed the relations between geometric shapes in architectural space and spatial decision making [17]. Hoever, a comprehensive quantitative description of the spatial acquisition process remains unclear which restricts architerctural deisgn evaluation.Limitations in Wayfinding Models

Some researchers show that familiarity with the environment influences strategy choice for individuals in wayfinding tasks [18]. With the state-of-art taxonomy in wayfinding tasks by Wiener, it is quite clear that existing research in wayfinding comes with the assumption of a certain degree of familiarity of the space [19]. Different levels of spatial knowledge acquired by the individual determines the wayfinding strategies, thus resulting in different wayfinding types [19]. However, it is acknowledged in the field of spatial cognition that individuals sequentially perceives information during wayfinding and the familiarity of the environment changes during the wayfinding process [20]. With this short coming, current wayfinding models become invalid in many cases when the individual slowly get familiar with the built environment.

2 A Spatial Knowledge Acquisition Model in Architectural Space

As can be seen from the overview of the limitations in the aforementioned research fields, a quantitative spatial knowledge acquisition model is needed. In this paper, a conceptual spatial knowledge acquisition model for architectural space is introduced based on the continuous cognition framework, which will finally lead to a dynamic computational model for wayfinding. In this model, three types of local information in architectural space are concluded to explain the relations between architectural space and human cognition process.

Because the spatial knowledge is acquired sequentially from local information in space [6], the useful information derived from architectural elements in architectural space has to be identified first. In the field of human cognition, these local cues are the discrete objects stored in the memory [14]. In architectural space, such local cues have social meanings. For example, a door is recognized and stored as a "door" in the memory rather than a panel with certain dimensions. The existence of such social meanings even affects the perception of unseen space. For example, it is true for most individuals that the perception of a row of empty chairs before a door would indicate it could be a meeting room rather than a locker room. Empirical findings have approved such impact from the background knowledge in the decision making during wayfinding [21] and the construction of spatial knowledge [22]. These local information derived from architectural elements is called local architectural cues by Sun in 2008 [23]. He suggested that local architectural cues are a type of information that is perceived from the three-dimensional geometric features of local architectural elements. Different information is retrieved from the architectural elements based on different tasks. In his modelfour kinds of architectural cues are retrieved: the architectural elements in the circulation system, the distance from the architectural elements to the individual, the scale of the architectural elements, and the angular positions of the architectural elements in the individual's field of view. Though his model bypasses the process of constructing spatial knowledge and the cues derived from the architectural elements directly decide the movement of the evacuees [24], the performance of the model is quite good. This good performance can be explained by the fact that leaving at the exits is the dominant rule in the decision making in emergency situations. Further studies by Chen developed this model into more complex room configurations [25] and also shows a good performance. These results proved that local architectural cues are essential to the individual's perception of the architectural space and the construction of spatial knowledge is task dependent.

For the construction of spatial knowledge in a general manner, there exist human cognition frameworks which could help to identify the essential types of local architectural cues. One framework by Siegel & White was introduced in the year 1975 [14]. Later, in 1998, Montello proposed an alternative framework which is believed to be more conceptually coherent and more consistent with research evidence [15]. This new framework, which was later called the continuous framework by Ishikawa [26], has received support from several studies, such as individual differences of spatial abilities [27, 28], sense-of-direction [29, 30]), neural correlates of spatial thinking [31] and in the developmental pattern of individual's spatial knowledge [26]. There are five tenets in this framework:

1. The metric configuration knowledge is acquired by first exposure to a novel place. (e.g. The distance between two doors in the wall is perceived (though roughly) when the subject sees them.)
2. As familiarity and exposure to places increases, the completeness of spatial knowledge continuously increases. (e.g. As the subject moves from the first floor to the top floor in a building, his/her familiarity gradually increases.)

3. Separately learned places are integrated into a more complex spatial knowledge. (e.g. When the chandelier in the atrium can be seen from two rooms at different levels of a building, the subject may get an idea of the relative position of both rooms.)
4. Individuals with equal levels of exposure to a place differ in the accuracy of their spatial knowledge. (e.g. People in a tourist group behave differently in their wayfinding abilities in a totally unfamiliar environment.)
5. Linguistic systems can be used to store non-metric spatial knowledge. (Some landmark information such as “a grocery store on the opposite of the destination” or “a red building at the end of the blocks” is stored in the subjects’ linguistic system and serves as a guidance in the wayfinding)

These five tenets shed light on the spatial information (local architectural cues) that should be retrieved for the construction of the individual’s spatial knowledge in architectural space. With the guidance of these five tenets, three types of architectural cues are concluded, namely (1) semantic information from architectural space, (2) metric information from architectural space and (3) reference frames from architectural space. The relations between these architectural cues and these five tenets are explained in the following section.

2.1 Semantic Information from Architectural Space

Relations with the Cognition Framework. Semantic information indicates the meaning of geometries in architectural space. This is in accordance with the fifth tenet. Hershberger argues, “There are few forms in architecture to which men do not attach some meaning either by way of convention, use, purpose, or value. This includes the very mundane realization that a wood panel approximately three feet wide by seven feet high is a Door, which can be used to go through from one space to the other.” [32] With a metaphor of languages, Zevi explains the feature of the architecture from the other art forms as its working with the “three-dimensional vocabulary” related to the human being’s behavior [33]. It is true that this semantic knowledge has a close relation to our linguistic system in wayfinding tasks. Existing cognition research showed that people learned landmarks through verbal descriptions or labels [34, 35]. Raubal showed that linguistic information could enhance wayfinding performance [36]. Because architectural space is filled with meaningful geometries such as windows, door, columns, stairs etc. , semantic information is an essential part in the construction of spatial knowledge in architectural space.

Relations with the Architectural Space. The mapping between the architectural components in the architectural space and the semantic knowledge is quite simple and straightforward. For English speaking individuals, a door component is mapped to the word “door” and stored in the linguistic system. Semantic information can be extracted from the dimensions of the objects and the geometric relations between objects in space. A rectangle with a width of 1.5 meters and a height of 2.3 meters could be a door. A door shall be enclosed by a wall and the wall shall be parallel with the ceiling and floor. Relevant research with autonomous robots could shed light how semantic information could be extracted from geometric information [37].

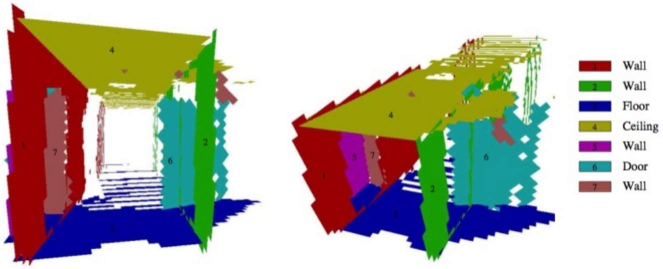

Fig. 2. Semantic information extraction according to the geometric features of the scene objects by Nüchter's team

2.2 Metric Information from Architectural Space

Relations with the Cognition Framework. The metric information indicates the geometrical properties of objects in space. This is in accordance with the first tenet. Because the metric information is critical in the integration of spatial knowledge and it's acquired on the first exposure of a place (empirical support from Ishikawa [26]), the metric knowledge has to be a critical part in the construction of spatial knowledge in architectural space.

Relations with the Architectural Space. The mapping between the architectural components and the metric information is also quite straight forward. This information is quite vague at first such as a "wide" door. However, it will be more precise after more exposure to the space and close to the actual dimensions of the architectural component. This is in accordance with the second tenet that the metric knowledge becomes more accurate after more exposures to the environment. As to the extraction of geometric information from architectural space, there are various methods to be referenced in the field of 3D robot mapping. Some fast mapping algorithms are available to extract dimensions of objects in architectural space by 3D scanning [38-40].

2.3 Reference Frames from Architectural Space

Relations with the Cognition Framework. Reference frames indicate the coordinate system of the perceived objects in the environment. This is in accordance with the third tenet, because it helps to integrate all the separate pieces of local information into spatial knowledge. Empirical findings support the existence of the reference frame when individuals construct their spatial knowledge [41]. Other research revealed that features such as the axis of symmetry, elongation, functional characteristics, or the viewpoint of the observer might provide a basis to select and anchor a reference frame for a particular figure or scene to help to construct the spatial knowledge [6]. In architectural space, the geometry of the spatial context can have a large effect on the preferred reference direction and thus on the preferred reference frame. For example, if observers have to learn a configuration of objects within a square room, they will have a much easier time retrieving the spatial directions of the objects when imagining themselves aligned with the room's two main axes parallel to the walls than when imagining themselves aligned with the two diagonals of the room [42]. Therefore, reference frame serves as a fundamental part in the construction of spatial knowledge.

Relations with the Architectural Space. The mapping of the reference frames to the architectural components requires more investigations. Though walls have been studied as to its role as the reference frames, the relations between reference frames and other architectural components such as windows, ramps and columns remain to be identified. Some of these relations potentially exist in common design guidelines for architects. For example, in architectural design, it is believed that an array of columns could lead to a strong sense of direction and it is expected that an array of columns is likely to be chosen as the reference frames in some cases. Though there are no existing algorithms to extract spatial reference frames from architectural space, the combination of extracting both semantic and geometric knowledge would help since the reference frames are chosen based on both types of information [43]. More experiments on how the common architectural components are interpreted as reference frames could shed light on a successful extraction of reference frames from architectural space.

3 Conclusion

Existing spatial representation models, human spatial cognition models and wayfinding models have limitations that follow from the assumptions underlying these models.

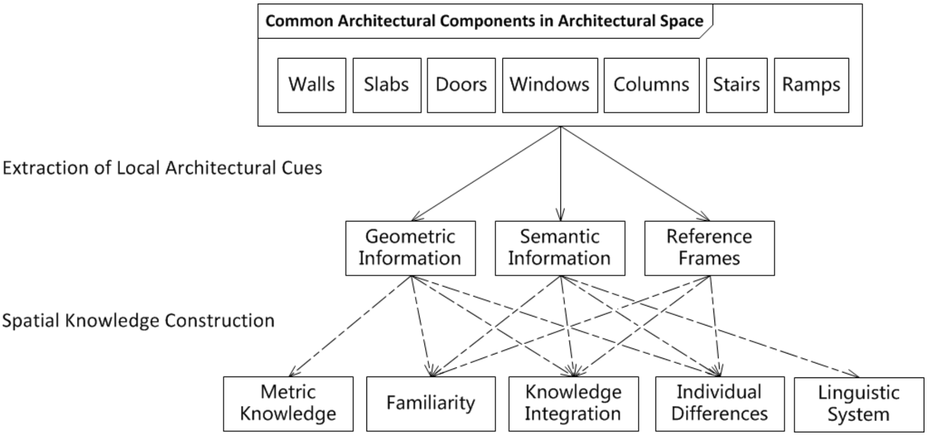

Fig. 3. The mapping of common architectural components and the five tenets in the continuous framework with the proposed three types of architectural cues

As a response to these limitations and assumptions, it is concluded that a computational spatial acquisition model is needed. For this purpose, a conceptual spatial knowledge acquisition model for architectural space is presented based on the continuous spatial cognition framework. Three types of local architectural cues are concluded to relate the architectural elements to the continuous spatial cognition framework. The proposed concept model will finally lead to a computational model which contributes to the field of spatial representation, human cognition and wayfinding. The overall structure of the presented cognition model can be seen in figure 3.

4 Future Works

In accordance with the continuous cognition framework, three types of architectural cues from the architectural space are concluded in this paper that constitute the essential information to be retrieved for the construction of individual's spatial knowledge in architectural space. With all these relations quantitatively described, a computational spatial knowledge acquisition model is developed. From the mapping in figure 3, some relations already have been investigated and some need to be identified in future works.

What's been done? The extraction of geometric information and semantic information from the architectural space has been explored in indoor GIS and robotics research [37]. Furthermore, with a BIM model in hand, it wouldn't be difficult to extract all the required geometric and semantic information.

What remains to be done? As can be seen in the previous sections, in the spatial knowledge construction phase (the second phase in Figure 3), there are many qualitative investigations but no quantitative models. For all the dotted lines in Figure 3,

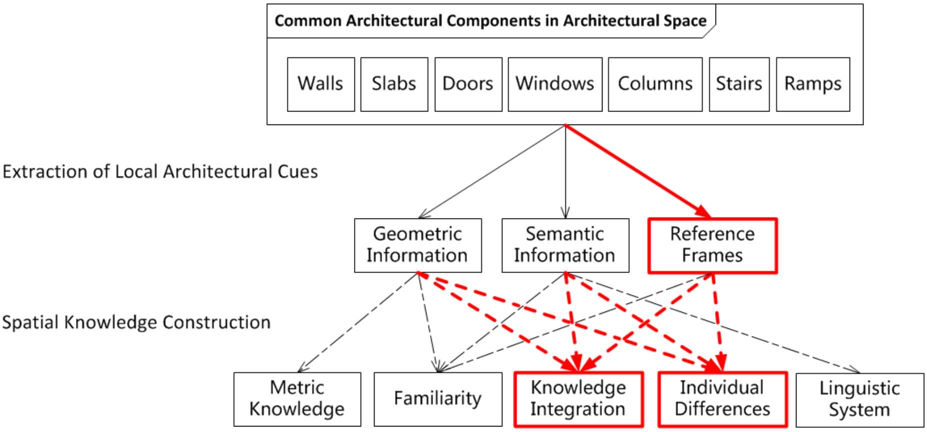

Fig. 4. Future works are highlighted for the construction of a computational spatial knowledge acquisition model

which represents connections between the continuous model and the extracted local architectural cues, the knowledge integration process has to be investigated first since it is needed to identify how local architectural cues construct the global knowledge of space. As individual differences are quite obvious in previous studies [26, 44], indivudual chrarcteristics need to be considered alongside with the knowledge integration process rather than considering “average people”.

For the highlighted relations in Figure 4, three future research tasks are concluded as follows:

- Extraction of reference frames from architectural elements: Examples of studies in the extraction of geometric and semantic information in architectural space are found in [37-40]. The extraction of the reference frames from architectural elements is crucial for understanding spatial knowledge construction.
- Computational representation of knowledge integration process: Examples of empirical studies on the roles of geometric, semantic and reference frames in the spatial knowledge acquisition process are found in [6, 21, 41, 45-47]. Further studies on how to represent these relations quantitatively will lead to a computational model of spatial knowledge acquisition.
- Consideration of individual differences in the retrieval of semantic information and reference frames: Though studies on the individual differences in the metric knowledge acquisition in urban context [26] and on the age differences in choosing the reference frames in outdoor spaces exist [44], more research is needed on the individual differences in the context of architectural space.

Acknowledgements. This work is supported by National Natural Science Foundation of China (project granted ID 51008212).

References

1. Lynch, K.: The image of the city. MIT press (1960)
2. Weisman, J.: Evaluating Architectural Legibility Way-Finding in the Built Environment. Environment and Behavior 13, 189–204 (1981)
3. Passini, R.: Wayfinding in architecture. Van Nostrand Reinhold Nova York (1992)
4. Peponis, J., Zimring, C., Choi, Y.K.: Finding the building in wayfinding. Environment and Behavior 22, 555–590 (1990)
5. O’Neill, M.J.: Effects of signage and floor plan configuration on wayfinding accuracy. Environment and Behavior 23, 553–574 (1991)
6. Werner, S., Schindler, L.E.: The Role of Spatial Reference Frames in Architecture Misalignment Impairs Way-Finding Performance. Environment and Behavior 36, 461–482 (2004)
7. Hillier, B.: Space is the Machine. Cambridge University Press, Cambridge (1996)
8. Gibson, J.J.: The ecological approach to visual perception. Lawrence Erlbaum (1986)
9. Davis, L.S., Benedikt, M.L.: Computational models of space: Isovists and isovist fields. Computer Graphics and Image Processing 11, 49–72 (1979)
10. Batty, M.: Exploring isovist fields: space and shape in architectural and urban morphology. Environment and Planning B 28, 123–150 (2001)

11. Turner, A., Doxa, M., O'sullivan, D., Penn, A.: From isovists to visibility graphs: a methodology for the analysis of architectural space. Environ Plann. B 28, 103–121 (2001)
12. Hillier, B., Hanson, J.: The social logic of space. Cambridge University Press, Cambridge (1984)
13. Peponis, J., Wineman, J., Rashid, M., Hong Kim, S., Bafna, S.: On the description of shape and spatial configuration inside buildings: convex partitions and their local properties. Environment and Planning B 24, 761–782 (1997)
14. Siegel, A.W., White, S.H.: The development of spatial representations of large-scale environments. Advances in Child Development and Behavior 10, 9–55 (1975)
15. Montello, D.R.: A new framework for understanding the acquisition of spatial knowledge in large-scale environments. Spatial and Temporal Reasoning in Geographic Information Systems, 143–154 (1998)
16. Ben-Yehoshua, D., Yaski, O., Eilam, D.: Spatial behavior: the impact of global and local geometry. Animal Cognition 14, 341–350 (2011)
17. Wiener, J.M., Hölscher, C., Buechner, S., Konieczny, L.: How the Geometry of Space controls Visual Attention during Spatial Decision Making. In: Proc. Annual Meeting of the Cognitive Science Society (Year)
18. Hölscher, C., Meilinger, T., Vrachliotis, G., Brösamle, M., Knauff, M.: Up the down staircase: Wayfinding strategies in multi-level buildings. Journal of Environmental Psychology 26, 284–299 (2006)
19. Wiener, J.M., Büchner, S.J., Hölscher, C.: Taxonomy of human wayfinding tasks: A knowledge-based approach. Spatial Cognition & Computation 9, 152–165 (2009)
20. Shirabe, T.: Information on the consequence of a move and its use for route improvisation support. Spatial Information Theory, 57–72 (2011)
21. Frankenstein, J., Brüssow, S., Ruzzoli, F., Hölscher, C.: The language of landmarks: the role of background knowledge in indoor wayfinding. Cognitive Processing, 1–6 (2012)
22. Haq, S., Zimring, C.: Just Down The Road A Piece The Development of Topological Knowledge of Building Layouts. Environment and Behavior 35, 132–160 (2003)
23. Sun, C., de Vries, B., Zhao, Q.: Measure the Evacuees Preference on Architectural Cues by CAVE (2008)
24. Sun, C., de Vries, B.: Automated human choice extraction for evacuation route prediction. Automation in Construction 18, 751–761 (2009)
25. Chen, Q.: A vision driven wayfinding simulation system based on the architectural features perceived in the office environment (2012)
26. Ishikawa, T., Montello, D.R.: 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, 93–129 (2006)
27. Allen, G.L., Kirasic, K.C., Dobson, S.H., Long, R.G., Beck, S.: Predicting environmental learning from spatial abilities: An indirect route. Intelligence 22, 327–355 (1996)
28. Meneghetti, C., Gyselinck, V., Pazzaglia, F., De Beni, R.: Individual differences in spatial text processing: High spatial ability can compensate for spatial working memory interference. Learning and Individual Differences 19, 577–589 (2009)
29. Hegarty, M., Richardson, A.E., Montello, D.R., Lovelace, K., Subbiah, I.: Development of a self-report measure of environmental spatial ability. Intelligence 30, 425–447 (2002)
30. Wen, W., Ishikawa, T., Sato, T.: Working memory in spatial knowledge acquisition: Differences in encoding processes and sense of direction. Applied Cognitive Psychology 25, 654–662 (2010)

31. Hartley, T., Maguire, E.A., Spiers, H.J., Burgess, N.: The well-worn route and the path less traveled: distinct neural bases of route following and wayfinding in humans. Neuron 37, 877–888 (2003)
32. Hershberger, R.G.: A study of meaning and architecture. University of Pennsylvania (1969)
33. Zevi, B., Barry, J.A., Gendel, M.: Architecture as space: how to look at architecture. Da Capo Press (1993)
34. Heather, M.G., Fernando, S., James, S., Josephine, F.W.: Do landmarks help or hinder women in route learning? Perceptual and Motor Skills 95, 713–718 (2002)
35. Pazzaglia, F., De Beni, R.: Strategies of processing spatial information in survey and landmark-centred individuals. European Journal of Cognitive Psychology 13, 493–508 (2001)
36. Raubal, M., Winter, S.: Enriching wayfinding instructions with local landmarks. Geographic Information Science, 243–259 (2002)
37. Nüchter, A., Surmann, H., Lingemann, K., Hertzberg, J.: Semantic scene analysis of scanned 3D indoor environments. In: Proc of the VMV Conference (Year)
38. Thrun, S., Burgard, W., Fox, D.: A real-time algorithm for mobile robot mapping with applications to multi-robot and 3D mapping. In: Proceedings of the IEEE International Conference on Robotics and Automation, ICRA 2000, pp. 321–328. IEEE (2000)
39. Thrun, S.: Robotic mapping: A survey. Exploring Artificial Intelligence in the New Millennium, 1–35 (2002)
40. Henry, P., Krainin, M., Herbst, E., Ren, X., Fox, D.: RGB-D mapping: Using depth cameras for dense 3D modeling of indoor environments. In: The 12th International Symposium on Experimental Robotics, ISER, pp. 22–25 (Year)
41. Rock, I.: Orientation and form. Academic Press, New York (1973)
42. Werner, S., Saade, C., Lüer, G.: Relations between the mental representation of extrapersonal space and spatial behavior. In: Freksa, C., Habel, C., Wender, K.F. (eds.) Spatial Cognition 1998. LNCS (LNAI), vol. 1404, pp. 107–127. Springer, Heidelberg (1998)
43. Gramann, K.: Embodiment of spatial reference frames and individual differences in reference frame proclivity. Spatial Cognition & Computation (2011)
44. McNamara, T.P., Rump, B., Werner, S.: Egocentric and geocentric frames of reference in memory of large-scale space. Psychonomic Bulletin & Review 10, 589–595 (2003)
45. Yeap, W.K., Jefferies, M.E.: On early cognitive mapping. Spatial Cognition and Computation 2, 85–116 (2000)
46. Klatzky, R.L., Loomis, J.M., Golledge, R.G., Cicinelli, J.G.: Acquisition of route and survey knowledge in the absence of vision. Journal of Motor Behavior (1990)
47. Loomis, J.M., Klatzky, R.L., Golledge, R.G., Cicinelli, J.G., Pellegrino, J.W., Fry, P.A.: Nonvisual navigation by blind and sighted: assessment of path integration ability. Journal of Experimental Psychology: General 122, 73 (1993)