Advancing the Understanding of Spatial Cognition by Considering Control

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Abstract

The ability to process spatial information is crucial for various tasks as diverse as, navigation, planning layouts, and managing abstract concepts. Accordingly, considerable effort has been spent on understanding how spatial cognition is realized in the human mind. These endeavors have, however, so far virtually neglected one important aspect of spatial cognition, namely control. In this contribution we show that neglecting control constitutes a serious lack in understanding spatial cognition. Moreover, we propose conceptions for computational cognitive models including control for two particular spatial cognition tasks. Besides constituting first approaches to integrating control and spatial cognition these models potentially allow giving a more detailed account of the respective spatial cognition phenomena than currently available theories.

Control in Spatial Cognition

The ability to process spatial information, reason about space, and communicate about it is crucial in various domains of human endeavor. Without this ability people would not be able to, for instance, navigate their environment, exchange knowledge about dangerous or attractive places, plan vacations, execute directed movements, etc. Apart from these domains spatial cognition has furthermore been shown to be essential for managing abstract concepts (e.g., Torralbo, Santiago, & Lupianez, 2006) and gaining scientific insight (Machamer, Darden, & Carver, 2000). Thus, spatial cognition plays an important role in virtually all human activity.

According to this importance there has been considerable effort to unravel how spatial information is processed in the human mind. For example, abundant experimental data exists on human performance in tasks like perspective taking (e.g., Avraamides & Kelly, 2005), navigation (e.g., Golledge, 1995), and architectural design (e.g., Verstijnen, Leeuwen, Goldschmidt, Hamel, & Hennessey, 1998). Such data has usually been analyzed and interpreted with respect to the types of representations and / or operations defined on these representations used during spatial cognition. By taking such a focus on representations and (corresponding) operations, researchers, so far, mostly (see Allen, 1999, for an exception) seem to have neglected a third aspect essential for understanding spatial cognition, namely control.

The necessity for taking control into account is nicely exhibited by work done in the philosophy of science. There it is a general observation that proper explanations of scientific phenomena need to include—though sometimes named differently—control aspects. For instance, in terms of the mechanisms approach to scientific explanation proposed by Machamer et al. (2000), to be able to understand a phenomenon it is not enough to consider only the entities and activities involved in the scientific phenomenon. As Bechtel (2005) remarks, “The secret (...) is to organize components appropriately so that their operations are orchestrated to produce something beyond what the components can do.” In addition to illustrating that control should be part of a proper explanatory description, Bechtel’s remark highlights the fact that control (which he terms “organize”, and “orchestrated”) might in some cases even be an indispensable aspect for arriving at a satisfactory explanation of some phenomenon.

Consequently, neglecting control in trying to understand spatial cognition and, thus, an essential part of human behavior, seems to be insufficient. It is not alone the (type of) representations and their associated processes which constitute the basis for human spatial cognition, but also how these representations and operations are organized. To the best of our knowledge, however, detailed accounts of control in spatial cognition are missing so far. This is not to say that existing models of human spatial knowledge processing (e.g., Gunzelmann, Anderson, & Douglas, 2004; Barkowsky, 2001) are realized without involving control mechanisms. Any computational model necessarily has some form of control mechanisms implemented, because otherwise it would not lead to reasonable results. However, these control mechanisms have been realized more as the result of this necessity than as the result of a careful consideration of the specifics of human control mechanisms in the respective tasks. Put differently, available control conceptions are rather unelaborate by-products of developing models which mainly focus on representations and operations.

In this contribution we will show that explicitly considering control in spatial cognition is directly relevant to gain a satisfactory understanding of spatial cognition and, thus, the available approaches are insufficient. Furthermore, we will propose conceptions for two computational models including control for two spatial cognition tasks. Since control has been virtually neglected so far in spatial cognition research, these models are the first to integrate aspects of both cognitive control and spatial cognition. In addition, the models potentially allow giving more detailed accounts of the modeled spatial cognition phenomena than previously proposed theories for these phenomena.

The remainder of this article is structured as follows: In the next section the phenomena observed in human imaginal perspective taking, existing explanatory approaches for this task, how considering control might improve the explanatory power of existing approaches, and first steps towards a computational cognitive model for imaginal perspective taking will be detailed. The subsequent section will comprise the same aspects, but for a different spatial cognition task, namely the apprehension of spatial terms. Finally, issues for future work will be highlighted in the conclusions.

Control in Imaginal Perspective Taking

As Rieser (1989) remarks, planning and executing actions when moving through an environment requires judging spatial relations in this environment from certain locations and / or orientations before the moving body actually is at the corresponding locations / orientations. Likewise, for example tele-operating a vehicle, giving and understanding route directions, or considering whether changing one's location will improve one's view on some audio-visual display may call for judging spatial relations from certain perspectives without moving the body into this perspective. Common to all these situations is that (a) one is inside the environment for which the spatial relations have to be identified and (b) the sensory information about the environment available is just the egocentric visual and auditory impression (i.e., in particular, a map-like bird's eye view is not available). The task of judging spatial relations in such situations from a different perspective than the bodily one has been termed *imaginal perspective taking* (*IPT* see May, 2004).

As illustrated by the above examples, IPT is essential for everyday life. Thus, IPT mirrors the importance of spatial cognition in general for human behavior (see above) and, accordingly, in order to understand how this ability is realized in the human mind numerous experiments have been conducted. The general setup of such experiments and their main results will be described in the next section.

Investigation of Imaginal Perspective Taking

Growing interest in understanding IPT has resulted in an abundant number of experiments (see e.g., Avraamides & Kelly, 2005; May, 2004; Farrell & Robertson, 1998; Easton & Sholl, 1995; Presson & Montello, 1994; Rieser, 1989). Although they differ with respect to the precise factors they are investigating, the general design is usually the same in these experiments.

A typical IPT experiment consists of two phases. In the first phase subjects are placed at a certain location with a certain orientation in an environment. Besides the participants there are a number of objects in the environment which surround the subject (see Figure 1; the location of the person is at the origin of the two arrows, her orientation is indicated by the solid arrow). The participants are told to memorize the locations of the objects. After the subjects have sufficiently learned the spatial arrangement the second phase begins[1]. In the second phase they are placed in the same environment and usually at the same location and orientation as in the first phase. This time, however, they are deprived of any visual or auditory information (e.g., by blindfolding and putting on headphones). The subjects are then asked to judge a number of orientation relations between themselves and the surrounding objects. Importantly, they often have to judge this relation as if they would be located or oriented differently than they actually are. For example, considering the setup shown in Figure 1 the subject might be asked to judge the relation of object 6 to herself as if she would be oriented to object 4 (the pretended orientation is indicated by the dashed arrow). The measures commonly used in such experiments are the times participants need to indicate and the accuracy (determined as degrees of angular deviation) with which they can indicate the asked for orientation.

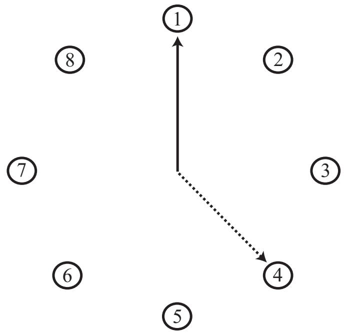

Figure 1: Prototypical experimental arrangement used in IPT studies.

Based on this general framework several factors have been varied in the particular experiments to elucidate the representations and processes used by humans during IPT. Studies differ, for instance, whether (a) they use irregularly or regularly arranged objects, (b) they test in small scale (e.g., a room) or large scale environments (e.g., a campus), (c) they test in familiar or unfamiliar (i.e., newly learned) environments, (d) a virtual or real environment is used, or (e) the participants have to indicate the asked for orientation verbally or by pointing. Regardless of such specifics, however, there are some general results occurring under virtually every experimental condition. First, judging relations from an imaginal perspective is harder, that is, takes more time and is less accurate, than judging relations from the actual perspective. This is true for both imaginal perspectives resulting from a change in orientation (the subject has to imagine facing in a different direction than he actually is) or a change in location (the subject has to imagine being in a different location than he actually is). Second, imaginal orientation changes seem to be more difficult than imaginal location changes. Third, the decline in performance observed with imaginal changes in orientation is linearly proportional to the angular difference between the actual and the imaginal orientation. Some studies, like the one by Easton and Sholl (1995), also point at a proportional relation between the performance in imaginal change of location and the distance between the actual and the imagined location. Yet, this relation seems to hold only under certain environmental / experimental conditions (cf. May, 2004; Rieser, 1989).

Existing Explanations

The prevalent explanation for the experimental results described in the previous section has been in terms of analogical rotation and translation processes (e.g., Sholl, 2001; Farrell & Robertson, 1998). Simply speaking, the general assumption is that humans are able to mentally rotate and / or translate

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[1] Sometimes the participants are tested in environments they already know from everyday life. The first phase is obsolete then.

themselves into the position requested for the current task and then can judge spatial relations from this (mentally taken) position. To give a more detailed account on how such mental rotation of oneself might be realized, several types of representation structures and processes have been proposed.

Sholl (2000), for example, has suggested that the human IPT ability relies on a set of separate allo- and ego-centric representation structures. The former mainly represents the object-to-object relations of the objects in the environment. The latter constitutes a viewpoint-dependent self-centered coordinate system which is superimposed / based on the allo-centric representation. This ego-centric coordinate system can be viewed as some kind of filter or mediator between the allo-centric representation and the ego-centric representation of space: By superimposing the ego-centric coordinate system over the allo-centric representation the object-to-object relations can be transformed into self-referenced coordinates (e.g., some object is in front of oneself).

Normally this ego-centric representation coincides with the actual bodily position in the environment, that is, objects in the environment which are in front of one's body will be represented as being in front of oneself. Importantly, however, Sholl (2000) assumes that it is also possible to dissociate the ego-centric coordinate system from the bodily position. In doing so, humans are able to transform the allo-centrically represented spatial information into an ego-centric representation assuming a position and / or orientation of oneself which is different from the bodily held position. According to Sholl it is precisely this ability to dissociate the self-centered coordinate system from the body which allows IPT. When asked to judge the relation between an object as if oneself would have a position and / or orientation which differs from the bodily one, humans need only rotate and / or translate their ego-centered coordinate system to the requested position and can then read off the spatial relation between themselves and the target object. Yet, rotating and translating the ego-centric coordinate system is not without cost. Similar to the conception of the mental rotation of objects proposed by Shepard and Metzler (1971), it is assumed that mentally rotating / translating the self-reference system is analog to rotating / translating one's body. This implies that the time needed to take an imaginal perspective is proportional to the angular disparity between actual and imagined perspective or the distance between actual and imagined position for rotation and translation, respectively.

These implications are supported regarding rotations, where the time needed to take the imaginal perspective grows proportionally with increasing disparity (see above). Yet, the empirical evidence regarding translations is ambiguous. Only some of the studies investigating translations (e.g., Easton & Sholl, 1995) have found a relation between distance and mental translation times, while other experiments could not replicate this finding (e.g., Rieser, 1989).

As the work by May (2004) (see also May, 2000, 1996) suggests these ambiguous results regarding translation tasks stem from a misconception of analogical transformation theories of IPT. Instead of positing that people mentally rotate or translate themselves, he assumes that the performance patterns observed in IPT studies are better explained by conflicts between incompatible action vectors. More precisely, in his conception the ego-centric pointing direction defined by the actual body position and orientation interferes with the requested (imaginal) pointing position and thus hampers judging spatial relations from the imaginal perspective. May assumes that the conflict is so much more severe the greater the angular difference between the actual and the imagined direction is. Several things are noteworthy with respect to this account. First, the conflict is assumed to occur at the level of action selection. Second, the difficulty of imaginal translations should depend only on the discrepancy of pointing directions between actual and imaginal perspective and not on the distance between actual and imagined position—a claim which has been supported by the experiments of May (2004). Third, May's conception can also easily account for the proportionally increasing difficulty of imaginal rotations with increasing rotation angle, since the angular disparity between actual and imagined pointing direction increases with rotational angle. Consequently, this conflict theory does not only reconcile contradictory experimental results, but also gives a more parsimonious account for IPT. Thus, May's theory seems to be superior to the analogical transformation approaches.

Nevertheless, on closer inspection of the theory, two things become apparent. For one, May's conception is still far from constituting a satisfactory explanation of human IPT. Besides positing that conflicts underlie the performance deficits in IPT the theory does not provide much detail on complementary aspects necessary to give a full account of human IPT. In addition, control seems to be crucial for explaining the human behavior in IPT tasks.

In the next section we will elaborate why and how control is essential for explaining IPT. Doing this will not only substantiate and corroborate our initial claim of the importance of considering control in spatial cognition, but at the same time result in a first conception for a computational model of IPT.

Including Control

The importance of control for explaining IPT becomes clear when considering research on task switching. *Task switching* (see Monsell, 2003, for an overview) refers to the ability of humans to change the task currently worked on and still perform the involved tasks quite accurately even if the stimuli and motor responses involved in the tasks are quite similar or even identical (called *bivalent* stimuli and responses). Since task switching requires the organized reconfiguration of mental resources, it is generally assumed that successful task switching heavily involves the control faculties of the human mind. Due to this relation task switching has been studied extensively (e.g., Allport, Styles, & Hsieh, 1994) to gain insight into human control mechanisms. In the light of the current discussion the following three results which have emerged from the studies are of major importance:

- Task execution is slower and more error prone just after a task switch. This decrement in task performance after switching is called *switch cost*.

- Switch cost can be reduced if the participants are allowed to prepare for a change in tasks before performing the (just changed to) task.

- Preparation for a switch does not eliminate switch cost completely. This has been interpreted such that a complete switch of tasks can only be executed after the stimuli to be processed in the scope of the task have been presented.

In the light of these three effects reconsideration of typical IPT tasks as described above reveals several similarities of IPT to task switching. To see this assume (a) that the case in which the imagined perspective coincides with the bodily perspective corresponds to the condition where the task is not switched and (b) that the case in which actual and imagined perspective do not coincide corresponds to the condition where the task has to be switched. Given these correspondences the similarities between IPT and task switching are the following: First, IPT uses bivalent stimuli and responses, because both the stimuli (i.e., the target objects) and the responses (indicating the direction to the target object) are used for all perspectives. Second, taking an imagined perspective (as task switching) is costly. Third, as shown by Sohn and Carlson (2003) the costs for taking an imagined perspectives can be reduced by a suitable preparation time. Fourth, preparation time does not completely abolish the cost for taking an imagined perspective (May, 2004; Sohn & Carlson, 2003; Sholl, 2001). Importantly, as the experiments by (May, 2004) exhibit the requested perspective can only be taken completely after the stimulus for the task (namely the target object) has been presented.

Given this correspondence between task switching and IPT as well as the fact that task switching is generally assumed to rely on control mechanisms implies that considering control is crucial for understanding human IPT behavior. Moreover, it allows drawing on already existing results from task switching research when developing accounts of IPT processes. Meiran (2000), for instance, proposed a computational model of task switching which is able to explain several of the empirically observed effects. Interestingly, in reproducing the effects the model explains task switching difficulties as mainly arising from a response conflict between the response for the previous task and the response for the current (i.e., just switched to) task. Transferred to the perspective switching domain this means that IPT difficulties mainly arise from the conflict between the response when the imagined and the bodily perspective are alike ("no switch") and the response when the two perspectives are not alike ("switch"). Not only does this correspond nicely to May's original conception, but also a study by Wang (2004) has recently supported this idea. It is because of this correspondence regarding the locus of conflict that the approach of Meiran (2000) seems especially suited as a starting point for developing a control model of IPT.

Of course, it is not possible to import the model of Meiran (2000) one-to-one into the IPT domain. For example, the representation format for stimuli and responses needs to be modified to account for the particularities of the IPT task. Furthermore, it is not immediately clear whether response repetition effects (i.e., the increased performance during task switching if the response is the same in two subsequent trials) and, thus, the corresponding model behavior also holds for IPT. Nevertheless, main parts of Meiran's model like the task dependent—and dynamically changing—weighting of the task sets and the computations used to select the final response seem well suited to model IPT. As a result, the presented analysis of IPT shows the relevance of control for understanding IPT. What is more, the analysis leads to a first detailed conception of a computational model for IPT[2].

Control in Spatial Term Apprehension

Another highly researched area of human spatial cognition is how people use language to communicate about spatial situations. Although the use of language in spatial cognition has many more facets (e.g., Tversky & Lee, 1998; Levinson, 1996), we will concentrate on the apprehension of spatial terms such as "above", "right", etc. More precisely, we will focus on the computational framework for spatial term use developed by Logan and colleagues (see, e.g., Carlson & Logan, 2001; Logan & Sadler, 1996). Although such a focus might seem restrictive given the multitude of approaches to spatial term apprehension, for this contribution such focusing seems necessary / expedient for at least three reasons. First, due to space limitations it is not possible to discuss more than one approach and its relation to control. Second, the considered computational framework has been proven to be a valuable framework for analyzing and accounting for empirical data. Third, the framework particularly nicely allows pointing out the relevance of control for understanding the processes involved in spatial term apprehension.

Based on a number of experiments the computational framework proposes that apprehending spatial terms comprises at least (a) spatially indexing (i.e., identifying) the relevant objects, (b) imposing a frame of reference (FoR) on one of the objects, and (c) based on this FoR determine the relation between the two objects. To illustrate this account, consider the following example: You are asked to verify the assertion "The fly is above the table" given a depiction containing a fly and a table (see Figure 2). According to Logan's account, to verify the statement you first need to find the table and the fly in the depiction. Once you found them you now need to judge the relation between them. To do this, Logan and Sadler (1996) posit, you superimpose a FoR on the table (indicated with dashed arrows in Figure 2). The FoR is superimposed on the table, because the fly has to be located with respect / reference to the table. Furthermore, FoRs are assumed to be coordinate system-like representations which can be anchored in objects and which structure the space on which they are imposed. Thus, by imposing a reference frame on the table the space surrounding the table is structured and objects populating this surrounding space can be assigned a spatial relation with respect to the table. In the scope of the example this means that once you have imposed the FoR on the table you can determine the spatial relation of the fly to the table and, as a result, verify the given statement.

Given this conception the need for and importance of control for understanding the use of spatial terms stems from the fact that there are situations in which more than one (type

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[2] At first sight it may seem that this is not a first detailed conception, since Hiatt, Trafton, Harrison, and Schultz (2004) and Gunzelmann et al. (2004) have already proposed computational models of perspective taking. Yet, the former seems to be more a cognitively inspired technical solution than a cognitive model and the latter does model a task which differs regarding important aspects from IPT (e.g., a map-like view of the environment is continuously visually available).

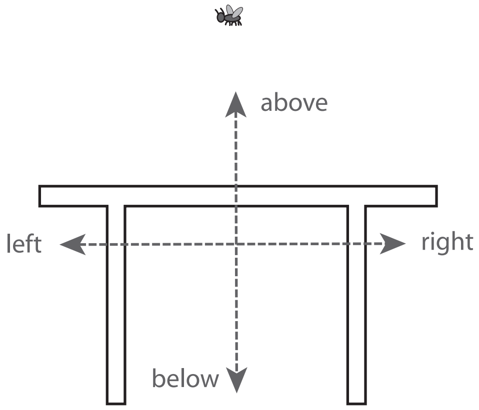

Figure 2: An example situation for assigning / verifying spatial terms.

of) FoR can be superimposed on the reference object. Considering again the above example at least three FoRs—which correspond to the three FoRs proposed by Levinson (1996)—could be employed to verify the assertion: First, one could use the intrinsic reference frame of the table where the above-below axis runs parallel to the legs of the table. Second, one could also use a relative FoR where the above-below axis coincides with the spine. Finally, a third alternative would be to use an absolute reference frame. In an absolute FoR the above-below axis coincides with gravity or cardinal directions. As a result, if several FoRs are potentially available, the selection of one of the FoRs becomes an essential aspect of the apprehension of spatial terms. In particular, as Carlson (1999) has shown (see also Carlson-Radvansky & Irwin, 1994; Carlson-Radvansky & Jiang, 1998) this selection exhibits the following properties:

- When using spatial propositions, initially, several FoRs are activated simultaneously.
- The activation of the different FoRs is automatic in the sense that people do not seem to be able to deliberately avoid activation of separate FoRs.
- Final selection of one of the rivaling FoRs seems to be realized by inhibiting the other (not selected) FoRs.

This pattern of properties of the processes involved in the selection of FoRs strongly suggests the relevance of control to the use of spatial terms, since it parallels observations in tasks usually assumed to largely involve control mechanisms. The Stroop task, for instance, has been shown (see, e.g., Cohen & Huston, 1994) to exhibit nearly identical patterns of properties as those outlined above: Representations for word meaning and word color are activated simultaneously; activation of word meaning cannot deliberately be avoided; and final selection of one of the representations is realized by inhibiting the other. Following a similar argument as in the case of IPT this shows that considering control is crucial to obtain a complete and satisfactory understanding of the use of spatial terms. What is more, this correspondence also opens up possible approaches for developing a detailed account of one crucial aspect of human spatial term apprehension.

Due to the nature of the selection process winner-takes-all networks (i.e., networks in which the nodes inhibit each other and activate themselves through reflexive connections, cf. Hagan, Demuth, & Beale, 1996) seem to be especially suited for realizing a detailed account of the involved control mechanisms (see Schultheis, under review, for a more thorough argument regarding the appropriateness of winner-takes-all networks). As with IPT this first conception of a computational account will probably need to be adapted to the specifics of the use of spatial terms. Nevertheless, even this first conception of adapting existing computational principles constitutes a more detailed explanation of the mechanisms involved in the selection of FoRs during spatial term apprehension than those currently available.

Conclusions

Previous research in spatial cognition has mainly concentrated on identifying representations and processes but virtually neglected control. In this article it is shown that rather than investigating spatial cognition in isolation from control these two aspects of human cognition need to be considered together. A close analysis of two well researched spatial cognition tasks, namely imaginal perspective taking and apprehension of spatial terms, revealed that in both tasks control processes can be assumed to play an important role. As a result, trying to understand human spatial cognition without considering control seems to be unreasonable.

In response to these observations we conceptualized two computational models for the two spatial cognition tasks. Importantly, these two models take into account control aspects and thus realize first detailed accounts integrating control and spatial cognition. Besides being integrated the two proposed models also potentially allow a more thorough explanation of human performance in both spatial cognition tasks than previous theories.

One major issue for future work is to further investigate to what extent the control mechanisms for particular spatial tasks differ from each other. Judging from the above analysis it would seem that the control mechanisms involved in spatial cognition might differ considerably for different spatial tasks. Yet, it seems premature to take a definite decision on this question at the moment—further investigations will have to show whether the control mechanisms in the different tasks are distinct or can be reconciled with each other or maybe reduced to a common basis. In exploring this issues, we plan to (a) refine the two proposed models, (b) extend the general ideas exhibited by the models to other areas of spatial cognition, and (c) identify further control principles which might be important for understanding spatial cognition.

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References

Allen, G. L. (1999). Children's control of reference systems in spatial tasks: Foundations of spatial cognitive skill? *Spatial Cognition and Computation*, *1*(4), 413 - 429.

Allport, A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umilta & M. Moscovitch (Eds.), *Attention and Performance XV.* Cambridge, MA: MIT Press.

Avraamides, M. N., & Kelly, J. W. (2005). Imagined perspective changing within and across novel environments. In C. Freksa, M. Knauff, B. Krieg-Brückner, B. Nebel, & T. Barkowsky (Eds.), *Spatial cognition IV.*

Barkowsky, T. (2001). Mental processing of geographic knowledge. In D. R. Montello (Ed.), *Spatial information theory (COSIT 2001).* Berlin: Springer-Verlag.

Bechtel, W. (2005). The challenge of characterizing operations in the mechanisms underlying behavior. *Journal of the experimental analysis of behavior*, *84*(3), 313 - 325.

Carlson, L. A. (1999). Selecting a reference frame. *Spatial Cognition and Computation*, *1*(4), 365 - 379.

Carlson, L. A., & Logan, G. D. (2001). Using spatial terms to select an object. *Memory & Cognition*, *29*(6), 883 - 892.

Carlson-Radvansky, L. A., & Irwin, D. E. (1994). Reference frame activation during spatial term assignment. *Journal of Memory and Language*, *33*, 646 - 671.

Carlson-Radvansky, L. A., & Jiang, Y. (1998). Inhibition accompanies reference-frame selection. *Psychological Science*, *9*(5), 386 - 391.

Cohen, J. D., & Huston, T. A. (1994). Progress in the use of interactive models for understanding attention and performance. In C. Umilta & M. Moscovitch (Eds.), *Attention and Performance XV.* Cambridge, MA: MIT Press.

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*(2), 483 - 500.

Farrell, M. J., & Robertson, I. H. (1998). Mental rotation and the automatic updating of body-centered spatial relationships. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *24*(1), 227 - 233.

Golledge, R. G. (1995). Path selection and route preference in human navigation: A progress report. In *Proceedings of the conference on spatial information theory.*

Gunzelmann, G., Anderson, J. R., & Douglas, S. (2004). Orientation tasks with multiple views of space: strategies and performance. *Spatial Cognition and Computation*, *4*(3).

Hagan, M. T., Demuth, H. B., & Beale, M. (1996). *Neural network design*. Boston: PWS Publishing.

Hiatt, L., Trafton, J., Harrison, A., & Schultz, A. (2004). A cognitive model for spatial perspective taking. In M. Lovett, C. Schunn, C. Lebiere, & P. Munro (Eds.), *Proceedings of the 6th ICCM.* Mahwah, NJ: LEA.

Levinson, S. (1996). Frames of reference and molyneux's question: Cross-linguistic evidence. In P. Bloom, M. Peterson, L. Nadel, & M. Garrett (Eds.), *Language and space.*

Logan, G. D., & Sadler, D. D. (1996). A computational analysis of the apprehension of spatial relations. In P. Bloom, M. Peterson, M. Garrett, & L. Nadel (Eds.), *Language and space* (chap. 13). MA: M.I.T Press.

Machamer, P., Darden, L., & Carver, C. F. (2000). Thinking about mechanisms. *Philosophy of Science*, *67*, 1 - 25.

May, M. (1996). Cognitive and embodied modes of spatial imagery. *Psychologische Beiträge*, *38*, 418 - 434.

May, M. (2000). *Kognition im Umraum.* Wiesbaden: Deutscher Universitäts-Verlag.

May, M. (2004). Imaginal perspective switches in remembered environments: transformation versus interference accounts. *Cognitive Psychology*, *48*, 163-206.

Meiran, N. (2000). Modeling cognitive control in task switching. *Psychological Research*, *63*, 234 - 249.

Monsell, S. (2003). Task switching. *TRENDS in Cognitive Sciences*, *7*(3), 134 - 140.

Presson, C. C., & Montello, D. R. (1994). Updating after rotational and translational body movements: coordinate structure of perspective space. *Perception*, *23*, 1447 - 1455.

Rieser, J. J. (1989). Access to knowledge of spatial structure at novel points of observation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *15*(6), 1157 - 1165.

Schultheis, H. (under review). A computational model of control mechanisms in spatial term use.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science*(171), 701–703.

Sholl, M. J. (2000). The functional separability of self-reference and object-to-object systems in spatial memory. In S. Ó Nualláin (Ed.), *Spatial cognition.*

Sholl, M. J. (2001). The role of a self-reference system in spatial navigation. In D. R. Montello (Ed.), *Spatial information theory (COSIT 2001).* Berlin: Springer.

Sohn, M.-H., & Carlson, R. A. (2003). Viewpoint alignment and response conflict during spatial judgement. *Psychonomic Bulletin & Review*, *10*(4), 907 - 916.

Torralbo, A., Santiago, J., & Lupianez, J. (2006). Flexible conceptual projection of time onto spatial frames of reference. *Cognitive Science*, *30*(4), 745 - 757.

Tversky, B., & Lee, P. (1998). How space structures language. In C. Freksa, C. Habel, & K. F. Wender (Eds.), *Spatial cognition. an interdisciplinary approach to representing and processing spatial knowledge.*

Verstijnen, I. M., Leeuwen, C. van, Goldschmidt, G., Hamel, R., & Hennessey, J. M. (1998). Creative discovery in imagery and perception: Combining is relatively easy, restructuring takes a sketch. *Acta Psychologica*, *99*, 177–200.

Wang, R. F. (2004). Action, verbal response and spatial reasoning. *Cognition*, *94*(2), 185 - 192.