Chapter 2
Natural Conditions of Spatial Cognition

Abstract The similar biological constitution of all humans and the fundamental similarities in their physical environments make it plausible to assume that there are structures of spatial cognition that do not vary between different cultures or over history, but constitute the foundation for all cultural manifestations of spatial knowledge. In order to understand the dependence of spatial thinking on culture it is important first to identify these structures. The chapter discusses the sensorimotor schemata that are formed in humans regardless of society and historical age in similar ways as with nonhuman primates. The examples presented are (1) the schema of permanent objects, which allows for successful handling of objects on a mesocosmic scale, and (2) the landmark model of larger-scale space underlying cognitive mapping skills and allowing for successful navigation through various types of environment.

Keywords Primate cognition · Spatial thinking · Cognitive mapping · Object permanence · Sensorimotor intelligence

The Object of Study

In order to understand how human spatial thinking depends on the cultural conditions present at different times in history it is of fundamental importance first to identify spatial abilities and corresponding cognitive structures that are *not* products of human culture, and accordingly not subject to historical change. These may be termed the *natural conditions of spatial cognition*. Starting from such an identification one may then ask how historical and present-day cultural manifestations of spatial thinking relate to this universal basis.

The natural conditions of spatial cognition are of a double origin. First, there are biological predispositions of the human species which also involve a cognitive dimension. Second, there are features of the physical environment in which each individual grows up that are so fundamental that they are independent of culture. In the first case, it is the mechanisms of biological evolution by which experience enters the formation of cognitive structures, in the second it is each individual's experience in ontogenesis. The two origins are closely entangled, however, since the ontogenetic

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unfolding of biological predispositions always takes place in a physical environment which exhibits certain universal features. While the question of the relation between the two origins shall not further concern us here, it is important to note that the idea of universal aspects in human spatial cognition does not in itself imply any kind of nativism.[1]

When trying to identify the natural conditions of spatial cognition we encounter a methodological problem. Cross-cultural studies help to identify aspects of spatial thinking that are human universals, i.e., aspects that do not depend on the particularities of any specific culture (for instance on the use of a particular language); yet, the universal aspects identified in this manner will include aspects that depend on the very existence of human culture (for instance on the presence of language altogether). From their birth on (and in certain respects even before that), human beings are immersed in their culture. They are born into a cultural *habitus* that shapes their social and physical experiences and thus potentially exerts an influence on their cognitive development. More importantly, they participate in specifically human modes of cultural learning.[2] As a consequence, when studying the ontogenesis of human cognition, it is practically impossible to abstract from processes of the individual's enculturation. Therefore, to unveil its natural conditions, human spatial cognition has to be compared to animal cognition as the cognition of beings without human culture. Of particular interest in this context is the cognition of nonhuman primates, since cognitively they appear closest to humans and are probably similar to our not-yet-human ancestors. The natural conditions of human spatial cognition arguably comprise their spatial abilities and the corresponding cognitive structures.[3]

To identify the natural conditions of spatial cognition the object of study must therefore be the spatial behavior of animals and humans (children and adults), and in particular of nonhuman primates. Of central relevance in this context are the abilities of *object permanence* and *cognitive mapping*. In the following, these abilities shall be described and explained in terms of their implications concerning the fundamental structures of human spatial cognition.

Example: Object Permanence

Object permanence is what developmental psychologists call the mental construction of objects as entities independent of the self, which are understood to exist in a definite location or move along a definite trajectory in space. Studies in developmental psychology suggest that what may be called the *schema* of permanent object is not

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[1]For a critical discussion of 'nativist' approaches, see, e.g., Tomasello (1999, 48–51).

[2]For an explanation of cultural *habitus*, see Tomasello (1999, 78–81); for that of cultural learning, see Tomasello (1999, 61–70), who relates these human modes of learning to the conception of others as intentional beings and argues that its development begins around the ninth month.

[3]For a more critical discussion of comparisons between animal and human spatial cognition, see Hazen (1983).

present at the time of a child's birth, but only develops during the first two years of childhood.[4]

The construction of the schemata of object on the one hand and space on the other are indissociable, as space can only be constructed concurrently with objects and vice versa.[5] No change in our perceptions could be understood as a change of place or position of something if there were no unchanging objects. On the other hand, for something to be an object it must necessarily occupy a certain space, i.e., be at a certain location and have a certain shape and size. To be able to understand certain changes as arising from one's own motion relative to the objects, it is furthermore necessary to conceive of one's own body as being positioned in a common space with the objects.

Following Piaget one can distinguish six stages of sensorimotor development, which describe the progressive dissociation of the objects and their spatio-temporal trajectories from the subject's activities.[6] We will particularly focus on the last three stages.

At the beginning of the development 'space' is heterogeneous in the sense that the spatial aspects of different senses and actions (oral space, visual space, auditory space, tactile space, the space of body positions, etc.) are not coordinated and thus not integrated into one structure. When the ability to grasp what is seen develops, this leads to the construction of schemata of action under visual control and the perceptual constancy of shape and size. The changes in the perception of bodies in motion (or changes perceived when the subject's body is in motion) are no longer understood as transformations of the 'objects', but rather as changes in perspective. A feeding-bottle, to mention one of Piaget's examples, is turned around by the infant in order to find the rubber teat, indicating the construction of the permanent object, with all of its parts being conserved.[7] Changes in body position are then gradually differentiated from changes of state. These developments can be considered the beginning of object permanence.

At this stage, however, infants seek a hidden object where they last found it and not where they saw it vanish.[8] Piaget interprets this finding to the effect that the object is still only a part of a situation characterized by the successful action, i.e., there is no object independent of action or at least no continuous trajectory of a body

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[4]For a definition of the concept of schema, see, for instance, Piaget (1983, 180–185). A different definition is given in Neisser (1976, 51–57). Below we will introduce the concept of *mental model* to describe relevant cognitive structures.

[5]See Piaget (1959, in particular 97–101).

[6]Various empirical studies have been devoted to testing Piaget's theory of cognitive development, complementing and correcting it in many respects. But while some of the interpretations have been at great variance with Piaget's views, the evidence does not seem to refute Piaget's overall scheme as outlined here. For a review of much of the literature and a critical discussion of post-Piagetian work on spatial cognition, see Newcombe and Huttenlocher (2003).

[7]For example Piaget (1981, 110–111).

[8]This behavior is often referred to in the psychological literature as the *A-not-B error*, 'A' denoting the location where the object was previously found and 'B' the one at which it vanished; see, e.g., Piaget (1981, 109–110) and Newcombe and Huttenlocher (2003, 53–71).

in space.[9] This stage of the construction of objects, usually referred to as *stage four*, and reached by human infants towards the end of their first year, may therefore for our purposes be called the *stage of action-bound locations*.

At the next stage (*stage five*), infants start proactive enquiry and systematic observation. They seek a hidden object based on the perceived displacement, i.e., they no longer search for it where they last found it, but rather where they saw it vanish. They are not able, however, to infer the position of an object that has been moved outside their view. This stage, reached by human infants at about the beginning of their second year, is here called the *stage of perception-bound locations*.

Stage six, by contrast, may be referred to as the *stage of perception-independent locations*. It is reached when the infant systematically seeks for a hidden object and does so exclusively at locations to which the object can possibly have moved. For instance, when an object is moved under a cover along a row of boxes and put into one of them, stage six ability means that the infant seeks for the object only in those boxes into which the investigator can possibly have put it. This ability therefore involves the mental representation of the displacement or trajectory of an object even if it cannot be seen while it is being moved.

In adult humans the abilities that indicate full development of object permanence appear to be universal. While there are indications that the speed of development varies, not only between individuals but between whole cultures, there are no studies known to me that would deny this ability for the members of any culture. Most studies do in fact take these abilities for granted.[10]

Object permanence skills have further been proven for many animal species.[11] In various studies it has been tested whether nonhuman primates and other mammals are able to locate objects when they have witnessed how they were hidden and if they can infer the location of an object that has changed place outside their view. A survey of the studies indicates that all primates and at least some nonprimate mammals (cats and dogs in particular) possess stage four and five skills of object permanence, i.e., they apprehend perception-bound trajectories.[12] To test whether primates possess stage six skills and apprehend perception-independent trajectories, an object is hidden, e.g., in a small box, which is then moved under several covers. From the observed seeking behavior of the animal it can then be concluded whether it can infer the possible location of an object that has been moved outside its view. Stage six skills have been proven rigorously for only a few primate individuals. Among nonprimate mammals, dogs possess these skills, while cats fail to do so.[13]

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[9] For a detailed discussion of this stage, see Piaget (1959, 44–66).

[10] See the discussion in Dasen and Heron (1981, 303–307).

[11] For a survey of the spatial abilities of nonhuman primates, see Tomasello and Call (1997).

[12] Tomasello and Call (1997, 41–42).

[13] According to Tomasello and Call (1997, 46), many studies which suggest stage six skills have not employed appropriate control procedures. One may speculate that the occurrence of stage six abilities depends on the specific needs of an animal species, e.g., when following prey or when avoiding predators (Tomasello and Call 1997, 55).

There is thus clear evidence that the sensorimotor schemata of object permanence in general, and the ones underlying stage six abilities in particular, are not unique to humans. On this basis one may argue that they belong to the natural conditions of human spatial cognition.

Action and perception under the control of the schemata of object permanence imply spatial structures among which there are the following:

- *Dichotomy of objects and spaces*: Objects are tangible (albeit not always reachable), and between them there are non-tangible (i.e., 'empty') spaces.
- *Definiteness and exclusivity of place*: Every object is in a place and always in one place at a time. No other object can be in the same place at the same time.
- *Three-dimensionality of objects and spaces*: Objects are extended in such a way that different sides of an object are perceptible from different perspectives. There is a concealed backside of each object (like the feeding bottle's rubber teat in Piaget's example). The spaces between objects are likewise extended, allowing for objects not only to be located side by side, but also to obstruct the view to another object.
- *Distinction of vertical direction*: There is one direction distinguished by the tendency of most objects (including one's own body) to fall down or to resist lifting.
- *Continuity of object trajectories*: The mutual spatial relations of objects, including one's own body, may change, i.e., there is motion. The trajectories of motions are continuous, i.e., there are no 'jumps': objects do not vanish in one place and re-appear in another, but pass through all intermediate places during the motion. Stage six abilities indicate that the schema of permanent object implies continuous trajectories regardless of whether they are perceived or not.

Example: Cognitive Mapping

Besides the smaller-scale skills related to object permanence, humans develop sophisticated abilities of spatial orientation on larger scales. They can quickly accumulate spatial information about previously unknown territories; in known territories they can move flexibly, i.e., they can make detours and take short cuts that they have not previously made or taken; and they can optimize their routes by arranging the stations of their travel in a rational manner. They can integrate knowledge about landmarks with knowledge about the motion of their own body to construct route knowledge, and combine their knowledge about intersecting routes to obtain what may be called configurational knowledge: knowledge about the overall configuration of landmarks and their relations.[14] They are further able to make use of cues such as wind directions, the position of the sun, or distal landmarks. Following a large body of literature, these abilities are here referred to as *cognitive mapping*.[15]

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[14] Siegel and White (1975); Kitchin and Blades (2002, 89–90).

[15] See Kitchin and Blades (2002) for a recent account on cognitive maps which surveys a large part of this literature.

Evidence for cognitive mapping in human adults is abundant. Members of hunter-gatherer societies as well as inhabitants of modern cities construct cognitive maps and use them in their everyday orientation and navigation, even though the concrete techniques and abilities of spatial orientation vary widely over different societies and different ecologies.[16]

As is the case for object permanence, cognitive mapping skills are subject to ontogenetic development.[17] They appear to develop later than the former, though, which seems plausible given the limited mobility of young infants and also the fact that the use of landmarks arguably presupposes object permanence of at least stage four (action-bound locations). The later development of cognitive mapping makes it even more difficult than was the case with object permanence to disentangle the natural development of biological predispositions from processes of the individual's enculturation and assess the scope of natural conditions of spatial cognition within cognitive mapping. Again, the comparison with animal cognition may provide important clues.

Besides humans, various species of animals exhibit sophisticated performance in spatial orientation.[18] Striking spatial abilities are found in various species of birds and mammals, in particular also rodents. It was, in fact, in the context of studies on the orientation abilities of rats in mazes that the term *cognitive map* was coined. Edward Tolman and his collaborators convincingly demonstrated that the rats' behavior could not be fully accounted for solely by means of stimulus and response. Rather the rats' spatial memory of the maze had to be organized in such a way that they could draw inferences about alternative pathways they had not employed before.[19]

Dogs and other mammals have also been shown to be able to use detours and shortcuts.[20] Nonhuman primates, in particular, have been shown to be able to use spatial information in a flexible manner.[21] Chimpanzees, for instance, who were shown how food was hidden at several locations in a familiar environment were later able to retrieve most of the food, whereby they did not follow the order in which the food was placed, but an order that reflected a minimum-effort strategy. They could also be shown to first retrieve, using such a strategy, the kinds of food they preferred before they proceeded to less preferred food.[22] Hamadryas baboons, to give another example, were observed remembering the locations of important sites such as sources of water in their local environment, to use least distance strategies in their travel, and even to speed up when approaching a known site well before they could have perceived it, thus demonstrating that they knew where they were.[23]

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[16] See, e.g., Hazen (1983).

[17] See, e.g., Kitchin and Blades (2002, 85–96).

[18] See various contributions in Pick and Acredolo (1983).

[19] Tolman (1948).

[20] See, for instance, Fabrigoule (1987).

[21] See Tomasello and Call (1997, 28–39) for a survey of the evidence for different primate species.

[22] See Menzel (1973). Menzel (1987) discusses the interpretation of these findings in terms of cognitive mapping.

[23] Sigg and Stolba (1981).

We can summarize these findings to the effect that the basic human cognitive mapping skills—just as object permanence skills—are not indicative of a peculiarity of human cognition but are among its natural conditions[24]:

> Overall, primates have the general mammalian spatial skills of cognitive mapping and object permanence […]. […] It is also unlikely that humans have any special skills in these domains of spatial cognition. They too possess the general mammalian skills of cognitive mapping and object permanence (with clear stage 6 skills early in ontogeny) .

The cognitive mapping skills imply fundamental spatial structures such as the following:

- *Dichotomy of movable and unmovable objects*: Some objects can be moved or move by themselves (e.g., conspecifics); other objects cannot be moved, i.e., they have a fixed location (e.g., trees). These latter objects thus define a ground against which one's own motion and the motion of other objects is perceived.
- *Focus on plane of movement*: The space of movement (structured by a network of landmarks, places, and regions) mostly lies within a more or less horizontal plane. (The additional importance of the vertical depends on the mode of life in particular ecologies such as living on different levels of a forest, of a mountainous region, or of a city with multi-story buildings.)
- *Path-connectedness of plane of movement*: The topology of the plane of movement is path-connected, i.e., between any two locations there is a path connecting them (otherwise it would not be a plane of movement). Generally, there may be different paths along which one may arrive at the same location and one may travel along a closed path and come back to one's initial location, even in cases where the path encircles obstacles that cannot be overcome (e.g., trees, mountains, river sections, or buildings).
- *Dependency of effort on path taken*: The effort it takes to get from one location to another generally depends on the path taken.

The Character of Spatial Knowledge

What is the epistemic status of the natural conditions of spatial cognition? It has been argued here that these conditions are rooted in sensorimotor intelligence, which is characterized by a close relation between cognition and concrete action.[25] The development of sensorimotor activity, roughly spanning the first two years of human

[24] Tomasello and Call (1997, 55–56). There are further studies pointing to similarities in animal and human spatial cognition. Thus, Foreman et al. (1984), who carried out experiments with pre-school children in a so-called radial maze, an arrangement previously used in experiments on spatial abilities of animals, have pointed to remarkable similarities between pre-school children and well-trained nonhumans in the performance of certain spatial tasks. This fact was interpreted to suggest a similarity of the role of visuospatial cues in the development and use of cognitive representations of space and the underlying processes across species.

[25] See Piaget (1981, 107–116); Piaget (1959, 86–96); Piaget and Inhelder (1956, 5–13).

life, involves the reflexes, grows to include habits, and culminates in the emergence of practical intelligence. In the course of this development, sensory data are assimilated to cognitive structures called *schemata of action*, which are in turn accommodated to the increasing amount of sensorimotor experience. The result is an increasing coordination, generalization, and differentiation of schemata of action which constitute human sensorimotor intelligence.[26]

It is important to note that the implied spatial structures described in the two preceding sections are not themselves objects of thought. They allow for successful action, but there is no indication that the related spatial abilities imply any consciousness, i.e., any reflection upon the schemata controlling the actions, and thereby go beyond the sensorimotor realm.[27] Thus, without the *dichotomy of objects and spaces*, no object could be perceived or grasped. Without the *dichotomy of movable and unmovable objects* no stable mental representation of the environment was possible. Without the *three-dimensionality of objects and spaces* no change in the visual image could be understood as a change of perspective. But while these structures allow for spatial inferences to be drawn, they do so only in the context of action and perception and are otherwise inaccessible to the actor.[28] This becomes clear, for example, when school children who successfully find their way from home to school and back are unable to represent these routes in a map-like fashion.[29] Another example is provided by the well-attested difficulties of children to rotate a landscape in their minds and describe how it would look from a different point of view.[30]

In particular, there is no indication of symbol use or the dependence of spatial cognition on external knowledge representations in general.[31] Accordingly there are also no concepts of space. The cognitive structures forming the natural conditions of spatial cognition common to all humans do not represent general, or abstract, ideas,

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[26] See, e.g., Piaget (1981). See also Damerow (1998, 248).

[27] They rely on what Piaget has called *perceptional space* in distinction to *representational space*, which is built up only at the preoperational and operational stages (Piaget and Inhelder 1956, 3–43). See, however, Boesch and Boesch (1984, 168–169) who interpret some of their findings as evidence for concrete operational thinking in the spatial reasoning of nonhuman primates and suggest the existence of 'Euclidean' cognitive maps, relating to Piaget's distinction between topological, projective, and Euclidean space; see also Normand and Boesch (2009).

[28] It remains an open question to what extent the transfer of spatial abilities to novel and artificial contexts of action presupposes that the actor's understanding of the novel situation is one involving a representation of real space. For example, it may be doubted whether the fact that rhesus macaques, using a joystick, are able to anticipate the path through a computer-simulated maze (see Tomasello and Call 1997, 51–54) necessarily implies that they conceive of the maze as a representation.

[29] Piaget (1960, 3–26).

[30] See the classical experiment by Piaget and Inhelder (1956, 209–246). For a critical discussion integrating recent empirical results, see Newcombe and Huttenlocher (2003, 118–125).

[31] A possible counter example of symbol use in spatial communication among bonobos is discussed in Savage-Rumbaugh (1998, 161–165), but does not seem conclusive.

but depend on the specific contexts of action and perception. They are not to be found on the level of concepts but on that of the schemata controlling sensorimotor behavior.[32]

Besides the notion of schema of action we shall employ the concept of *mental model* in referring to these cognitive structures. The concept of mental model refers to internal knowledge representation structures that allow current experience to be processed by relating it to former experience. The structure of the model consists of *slots* and their mutual relations. The slots are filled by specific instances, i.e., by an input from the current situation fulfilling certain conditions required by the slot. But these slots may also have default fillings which are effective whenever appropriate current information is not available. The default fillings of slots is one way earlier experience is encoded in the mental model. In fact, the very structure of the model is a result of earlier accommodations to experience.[33] In this way, a mental model allows the perception of, understanding of, or even reasoning about, a situation whenever the situation can be assimilated to the model successfully—even in cases where the available information is incomplete. A major reason to introduce the concept of mental model here, and not simply speak of sensorimotor schemata, is that mental models function on different levels of cognition. The sensorimotor and practical mental models inform the models functioning on higher conceptual and theoretical levels (and these may in turn have repercussions on the lower levels).[34]

The sensorimotor *mental model of a permanent object* is a mental structure into which sensory data are assimilated when objects are perceived and handled. For the assimilation to be successful, the shape, size, location, and position of the object must be identifiable. But they do not need to be constant in time. The sensorimotor schemata that underlie the model ensure that certain changes in perception are interpreted as changes of perspective, i.e., of the position of the object or one's own body in respect to it, rather than as changes of the object itself. As becomes clear from our discussion above, the sensorimotor model in its fully developed form further implies the mental representation of continuous trajectories.

To describe a range of abilities in large-scale spatial orientation, we have employed the term *cognitive mapping*. This term is widely used, but the precise character of the mental representation underlying the related abilities is a matter of controversy. In particular, it is not at all clear that this representation can be characterized as a bird's eye view of the environment as the term 'map' suggests. Just as the mental model of

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[32]We reserve the notion of concept to describe elements of knowledge structures that are somehow related to linguistic or otherwise symbolic representations, without implying, of course, that there was a one-to-one relation between concepts and words.

[33]For an introduction to the concept of *accommodation* (the adaption of mental structures to environmental inputs) and the complementary concept of *assimilation* (the adaption of environmental inputs to mental structures; see below), see Piaget (1981, 7–9 and *passim*).

[34]On the concept of mental model as understood here, see in particular Renn and Damerow (2007); see also various contributions in Gentner and Stevens (1983). The concept is akin to Marvin Minsky's *frames* (Minsky 1975).

object does not presuppose a three-dimensional mental image,[35] the mental representation of the large-scale environment need not take the form of a two-dimensional map.[36]

Here the corresponding cognitive structures shall again be described in terms of mental models. The *mental models of large-scale space* may be conceived of as networks of landmarks and their spatial interrelations. It is plausible to assume that the landmarks and their relations are part of a hierarchical structure, in which places and regions of different size are defined by reference to landmarks or other places and regions.[37] The landmarks, places, and regions are further endowed with contextual information about what is found there, e.g., kinds of food, water, predators and conspecifics, tools, and places to rest. The spatial relations between landmarks, places, and regions of different size involve topological information (inclusion, order along a route, proximity) as well as information on distances and angles. This latter information is given not in terms of numerical measures, of course, but rather in terms of sensorimotor experiences about variation in travel effort, about viewing directions to landmarks, and about perspectives. Configurations of landmarks, places, and regions can further be related to reference points outside the realm of motion such as the sun or distal landmarks like a large mountain, or to directions defined by features within the local environment such as a slope of the landscape or recurring winds. The landmarks that fill the model's slots are permanent objects or configurations of such objects, so that the elementary knowledge about objects in general (their permanence, their change of appearance with perspective and distance, etc.) applies to them. The structural relations between the slots contain the knowledge about the spatial relations among the landmarks. The individual realizations of the mental models of large-scale space are highly dependent on the concrete features of the respective environment, since they encode the experiential knowledge accumulated as the individual moves through this environment. Nevertheless, the basic structure applies universally. This universal structure will in the following be referred to as the *landmark model of space*.

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[35]It is the functioning of the model—for instance the way different perspectives are coordinated to make an object remain constant in size and shape under different views—that implies the three dimensionality. For a suggestion of how a three-dimensional cube and its transformations under different perspectives may be realized mentally without invoking a three-dimensional mental image, see Minsky (1975, 216–221), who uses coordinated *frames*. A more comprehensive discussion of three-dimensional vision is found in Marr (1982).

[36]Objections against imputations of the use of cognitive maps, in particular when simpler explanations of the spatial abilities are available, are raised, for instance, by Tuan (1975) and Bennett (1996). Recently, Wang and Spelke (2002) argued against the concept of cognitive map, emphasizing the human use of navigation techniques such as path integration, which are also found in insects and spiders and imply no more than the mental representation of one vector. It seems, however, that the presence of more 'momentary' and 'egocentric' representations does not at all preclude the build-up of more enduring and comprehensive mental representations. On the relation of these two types of representations, see, for instance, Cornell and Heth (2004).

[37]See Gärling et al (1985) for a detailed description of the possible components cognitive maps are made of.

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