Spatial Reasoning

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Introduction

Spatial reasoning is the mental transformation of spatial knowledge. Such transformation is an integral component of everyday cognition, occurring within a variety of domains such as attention, memory and language, and across a variety of tasks, spatial and non-spatial alike. The structure of this chapter is as follows. In Section 1 we discuss the core components of spatial reasoning, including spatial representations, spatial processes and spatial memory. In Section 2 we discuss basic spatial tasks, including navigation, giving directions, imaginal perspective taking, spatial inference, and visualization. In Section 3 we discuss the broader influence of space beyond such basic spatial tasks, as reflected in spatial compatibility effects, the use of space to understand abstract concepts, and reasoning by spatial analogy. In Section 4, we discuss neural systems that underlie our spatial abilities, individual differences, and learning. Finally, in Section 5, we discuss open questions for future research.

Section 1. Core Components of Spatial Reasoning

The transformation of spatial information requires three components: 1) the representation of this information; 2) a set of processes that operate on these representations; and 3) a memory system that encodes and maintains the spatial information and its transformations.

Section 1.1. Spatial Representations

Spatial reasoning often relies on existing knowledge about the spatial environment. For example, imagine that you are home but need to go to the airport to catch a flight to begin your vacation. Your reasoning about how to accomplish this goal requires knowledge about a number of spatial relations. For example, you need to find your way out of your house; you need to plan a driving route to the airport; and once there, you need to park your car, noting its location for when you arrive back at the airport after your trip. The way in which the spatial information is represented for each of these pieces of information may influence the way in which that information is used and accessed. For example, if in planning your route to the airport, you rely on your memory of other trips to the airport, you may have difficulty if you encounter a detour that forces you to construct a novel (unexperienced) route. Two important components of spatial representations are their format, and the spatial reference frames that are used to organize the information.

Section 1.1.1. Format

Spatial representations of well-learned environments that represent information in a survey or birds-eye perspective are commonly referred to as *cognitive maps* (Tolman, 1948). It was initially assumed that these cognitive maps were similar to 2D maps of the environment, such as a floorplan of your home or a city map showing your house, traffic routes, and the airport. An important feature of this type of representation is that it is spatio-analogical. This means that the spatial relations between entities within the environment are represented by portraying the parts representing these entities in the same spatial relations (Sloman, 1975). For example, the intersection of two streets in an environment is represented on a map by showing that the two lines that represent the streets intersect. Similarly, two buildings that are next to each other are represented on a map in a corresponding adjacency. Support for this spatio-analogical property of cognitive maps is found in research on spatial processes (see Section 2) and spatial inferences (see Section 4).

However, the label “cognitive map” may not always fit perfectly for these types of representations. First, mental representations exhibit a number of inaccuracies and distortions not commonly found in external 2D maps. Distances may be represented asymmetrically, with the distance from your house to the airport not necessarily considered the same as the distance from the airport to your house (Sadalla, Burroughs, & Staplin, 1980). Further, distances between objects within a given region tend to be underestimated, whereas distances between objects in different regions tend to be overestimated (McNamara, 1986). Finally, directions are often distorted toward right angles, leading to a bias to represent angles as closer to 90° than they actually are (Moar & Bower, 1983) and a bias of to remember regions as aligned (Tversky, 1981).

Second, a spatial representation of a given external environment may actually correspond to a set of multiple representations, each corresponding to a different part of the environment, rather than there being a single all-inclusive representation (Brockmole & Wang, 2002; Tversky, 1993; Lynch, 1960). For example, there may be one spatial representation that corresponds to your living room, and another representation that corresponds to your kitchen. These representations are often partially interrelated and overlapping, such that their combination yields a (distorted) representation of the overall environment. Given this fractionated nature, *cognitive collage* (Tversky, 1993) and *cognitive atlas* (Hirtle, 1998) are metaphors for human spatial representations that may be more accurate labels for this type of spatial representation.

Third, spatial representations are hierarchical in the sense that knowledge is organized in nested levels of detail (McNamara, 1986; Stevens & Coupe, 1978). The overall space that is represented is divided into several parts that can be further divided into subparts. Each of the (sub)parts is represented by one representational unit, and each division leads to a new (lower) level in the hierarchy. For instance, you may have a representation of your city that is divided into neighborhoods. Your neighborhood may be further divided into the locations of houses; your house may be further divided into its floors and rooms. It is assumed that spatial relations are usually only explicitly represented between entities within the same level of the hierarchy. Thus, the spatial relation between your living room and kitchen may be explicitly represented, but not the relation between the kitchen and other structures in the city.

Section 1.1.2. Reference Frames

The organization of and access to a given spatial representation relies on a reference frame that provides a means for distinguishing parts of that space. As such spatial reference frames are pervasive in any form of reasoning that involves spatial information. For example, we use reference frames when reasoning about how to get to the airport as quickly as possible, because we need to distinguish the locations of start, end, and intermediate points along the route. It is common to conceptualize a reference frame as a coordinate system that consists of a set of axes (vertical and horizontal) that parse space into distinct regions (Levinson, 2003; Logan & Sadler, 1996). For example, a compass rose on a map distinguishes the main cardinal directions of that space.

There are different types of reference frames, based on the type of information that is used as the basis for distinguishing the different regions of space. For cognitive maps that adopt a survey perspective of an environment, the distinction is based on environmental information, such as cardinal directions or key features of the environment. This type of reference frame is variably known as allocentric or absolute. A key feature is that information is represented independently of a person's orientation or location within the environment. An example would be spatially locating your kitchen as being to the west of your living room. In contrast, a reference frame may distinguish regions of space based on one's current location and perspective. This type of reference frame is variably known as egocentric or relative. An example would be spatially locating your kitchen as behind the living room, from the perspective of someone standing in the front doorway. Both kinds of reference frames are involved in human spatial reasoning (Mou, McNamara, Valiquette, & Rump, 2004; Sholl, 2000); Wang & Spelke, 2002). Egocentric frame seems to be more important for transient representations of immediately surrounding space, and allocentric frames seem to be more important for more enduring representations of larger scale spaces. In addition, egocentric and allocentric reference frames can be coordinated. For example, one may transform egocentric representations into allocentric representations for long-term storage, and may transform a portion of an allocentric representation back into an egocentric representation as needed. Developmentally, the ability to use an egocentric frame precedes the ability to use an allocentric frame (Acredolo, 1988; Piaget & Inhelder, 1960).

Section 1.2. Spatial Processes

Spatial representations are accessed and manipulated by spatial processes. For example, at the airport, imagine that you purchase a map of your destination so that you can plan your visit. To make optimal use of the information represented in the map you may want to rotate it to make sure you know which way to turn after leaving the airport to get to your hotel; to move it in different ways, so that the current area of interest is right before you; and to direct your gaze and attention to different locations on the map such as tracing the street route from the airport to your hotel. Although all the spatial information is contained in the map, you can only make suitable use of this information by employing a set of spatial processes. As such, in combination with representations, processes are paramount for making the relevant information available for spatial reasoning. Three prominent spatial processes are mental rotation, mental scanning, and mental translation.

Section 1.2.1. Mental Rotation

Mental rotation is a process that changes the orientation of a spatial representation. A common example is when you try to imagine whether a piece of luggage may fit at a different orientation into your partially filled car trunk. This process of mentally changing a representation's orientation is called rotation because the performance characteristics of this manipulation are similar to characteristics for a comparable physical rotation. For example, the time needed for conducting a mental rotation increases monotonically and often linearly with the degree of rotation. Just as physically rotating an object 120 degrees would take longer than rotating an object 10 degrees, imagining it rotating 120 degrees takes longer than imagining rotating it 10 degrees. This monotonic relation between the magnitude of rotation and the time to rotate is quite robust and, starting with the study by Shepard and Metzler (1971), has been replicated many times (Cooper, 1976; Cooper & Shepard, 1973, Shepard & Cooper, 1982). This correspondence between physical and mental rotation offers compelling evidence for the spatio-analogical property of spatial representations (Shepard, 1984; see also Section 1.1.1).

Mental rotation can be applied to a wide range of representations. Empirical studies suggest that representations of single objects (Shepard & Cooper, 1982), representations of object arrays (Presson, 1982), representations of oneself (Farrell & Robertson, 1998; but see Sec. 2.3), and abstract representations (i.e., reference frames, Hinton & Parsons, 1981) can all be manipulated by mental rotation.

Section 1.2.2. Mental Translation

Spatial reasoning sometimes requires manipulating spatial location. For example, after mentally rotating a piece of luggage, it may be helpful to mentally imagine moving it to the open space in the partially filled trunk to check whether it will fit. The process by which such a change of location is achieved has been termed mental translation. Generally, the time required for a mental translation increases monotonically with distance, such that moving larger distances takes more time. This correspondence thus also supports the spatio-analogical nature of representations employed in spatial reasoning. As in the case of mental rotation, mental translation has been argued to be applicable to single objects (Larsen & Bundesen, 1998), representations of one's self (Easton & Sholl, 1995), and abstract representations (Graf, 2006).

Section 1.2.3. Mental Scanning

Mental scanning is a process that operates on spatial representations to enable inspection and exploration of particular parts of the representation. During this process, a circumscribed field of attention is shifted across the representation to make different parts of the representation more accessible. For example, after mentally rotating and translating a piece of luggage, you may want to more closely inspect the handles of the luggage to make sure that they will be accessible for removing the bag from the trunk when you arrive at the airport.

Research by Kosslyn and colleagues (Kosslyn, 1973; Borst & Kosslyn, 2008; Denis & Kosslyn, 1999) indicates that the time necessary to access a part of the spatial representation increases monotonically with increasing distance between that part and one's current focus. In other words, the time necessary to mentally scan across the representation is proportional to the distance that has to be scanned. Further studies have shown that valid and invalid cues to direct attention to imagined parts of a representation have similar impact on performance as cues to direct attention in visual perception (Griffin & Nobre, 2003; Finke & Pinker, 1982).

Section 1.3. Spatial Memory Systems

The third core component involved in spatial reasoning is memory for spatial information. However represented, spatial knowledge from previous experience can only be brought to bear during spatial reasoning if this knowledge is stored in one or more memory systems. Following a distinction common in cognitive psychology, spatial memory systems can be roughly divided into a more transient spatial working memory and a more enduring spatial long-term memory.

Section 1.3.1. Spatial Working Memory

Several studies (see Baddeley & Logie, 1999, for an overview) support the idea that human working memory is composed of a number of functionally specialized components. One of these components, called the visuospatial sketchpad, is thought to be responsible for the transient storage of visuospatial information. More precisely, the visuospatial sketchpad is assumed to consist of two distinct subcomponents that are responsible for different kinds of information. One component constitutes memory for visual detail such as color and shape or, more generally, the visual appearance of a scene. The other component constitutes memory for locations and sequences of locations that may result from movements through space. These two components have been shown to have functionally different characteristics. For example, Klauer and Zhao (2004) observed that the maintenance of location information in the spatial component was interfered with more strongly by a concurrent spatial (movement discrimination) task than by a concurrent visual (color discrimination) task. On the contrary, the maintenance of shape information was interfered with more by the visual task than by the spatial task. Furthermore, in contrast to the visual component, the spatial component is amodal in the sense that the stored spatial information need not arise from vision but can originate from various perceptual sources such as hearing (Vecchi, Monticellai, & Cornoldi, 1995).

Section 1.3.2. Spatial Long-Term Memory

Research on the enduring storage of spatial information has revealed two important characteristics of spatial long-term memory. First, the location of an object may be represented by noting its distance and direction relative to surrounding objects (Sholl, 2000). Consider, for example, your memory of the objects in your living room. You may encode the location of your couch as being a certain distance from the coffee table and the TV, and at a certain angular direction from these objects. Second, there are preferences for which objects you encode relative to each other. For example, you may encode the couch relative to the TV but not relative to the sideboard, based on the configuration formed by the objects and their relative locations. A task used to assess this characteristic is the judgment of relative direction task (Mou & McNamara, 2002). In this task, participants memorize a configuration of objects. They then are told to imagine that they are standing at one of the objects and facing a second object, and asked to point to a third object. Pointing responses are typically faster and more accurate for objects that are encoded relative to each other (face TV and point to couch) than objects that are not encoded relative to each other (face TV and point to sideboard).

Section 2. Basic Spatial Tasks

Spatial reasoning is a central component of our ability to successfully solve a number of problems that involve spatial information. This section highlights five basic spatial tasks---navigation, giving directions, perspective taking, spatial inference, and employing external visualizations---that rely on spatial reasoning and are frequently encountered in everyday life.

The described tasks are considered basic in the sense that performance in other, more complex spatial tasks such as architectural design involves employing several of these basic tasks in combination.

Section 2.1. Navigation

The goal to get from your living room to the airport is an example of a navigational task. Navigation consists of two main subtasks: *wayfinding* and *locomotion* (Montello, 2005). Wayfinding consists of the more cognitive components of the task, including planning, identifying one's current location, and updating that location as one moves. Locomotion consists of the more physical components of the task that enable you to move through the environment in a collision-free manner. We will focus on updating. There are two types of updating (Wang, 2003). The first type employs an egocentric reference frame (Section 1.1.2.) for representing one's location, and involves updating the direction and distance of objects relative to one's position with each movement through the environment. One example of such egocentric updating is dead-reckoning, in which the direction, speed, and time of one's own movement are tracked to maintain one's position relative to a starting point. For example, if you have walked one meter straight ahead, you know that the starting point is one meter directly behind you. If you then turn 90° to the right and walk another meter, the starting point is now 1.41 m to your back-right. Although it may seem difficult to do the computations required for dead-reckoning deliberately, a wide range of species including humans (May & Klatzky, 2000) have been shown to employ dead-reckoning during navigation.

The second type of updating employs an allocentric reference frame (Section 1.1.2.) for representing one's location in which one's position is updated relative to surrounding features rather than updated relative to the distance and direction of the navigational path. For example, if you walk toward a building in front of you by moving 1 meter straight ahead and then 1 meter to the right, you may note that you are now west of the building. While both types of updating are involved in navigation, there is ongoing debate about their relative importance (Meilinger, 2008; Montello, 2005).

Section 2.2. Giving directions

The task of giving directions provides information that allows a person who is unfamiliar with a particular environment to successfully navigate this environment (e.g., to get from an airport to a hotel). Formulating directions consists of three main steps (Lovelace, Hegarty, & Montello, 1999): First, the direction giver has to activate and access her spatial knowledge about the relevant environment. Second, based on this knowledge, a route has to be chosen. Third, the chosen route needs to be translated into a set of verbal instructions. Ideally, these three steps result in directions that are both accurate and easy to follow. Research on direction giving suggests coordination between direction giver and receiver that develops across exchanges, both with respect to the perspective that is adopted (Schober, 1993) and with respect to the labels used for landmarks (Brennan & Clark, 1996). There is also some suggestion that the landmarks that are selected and the way in which they are referenced depend upon a direction giver’s assessment of the familiarity of the receiver with the environment (Isaacs & Clark, 1987).

Section 2.3. Imaginal Perspective Taking

The ability to judge spatial relations from perspectives that are different from one’s current bodily perspective is important for everyday behavior. Suppose you are attending a talk by a colleague in an auditorium. Choosing a good seat will involve reasoning about how well you would be able to see the speaker if you imagine sitting at different open seats around the room. Such perspective taking has been termed imaginal perspective taking, and is more error prone and slower than judging spatial relations from the actual bodily perspective (e.g., Waller & Hodgson, 2006; Wraga, 2003; Kelly, Avraamides, & Loomis, 2007). This is particularly so in cases where the imaginal and the actual perspective differ in orientation. The larger the angular difference between the actual and the imaginal orientation, the longer and more inaccurate are relation judgments (Creem et al., 2001; Farrell & Robertson, 1998). A similar but weaker and less reliable decrement on performance is found for imaginal perspectives that differ in location from the bodily perspective. However, depending on the setup of the spatial layout involved in imaginal perspective taking, some experiments (Easton & Sholl, 1995; Rieser, 1989) have yielded no such performance decrement.

One explanation for the difficulties observable in imaginal perspective taking has been in terms of the spatial processes of mental rotation (Section 1.2.1.) and mental translation (Section 1.2.2.). According to this account, taking the imaginal perspective requires mentally rotating (in case of orientation change) and / or mentally translating (in case of a location change) oneself to the imaginal perspective in one's representation of the spatial layout (Sholl, 2000). Due to the analogical nature of these processes, imaginal orientation and location changes require time proportional to the angular difference and distance, respectively, between the imaginal and bodily perspective. However, it has also been suggested that such performance decrements in imaginal perspective taking arise from interference and not from mental transformations (May, 2004, Mou et al., 2004).

Section 2.4. Spatial Inference

New spatial knowledge can be obtained from already existing knowledge by drawing spatial inferences. If, for instance, you know that *Paris* is north of *Algiers* and that *London* is north of *Paris*, you can readily infer that *London* is north of *Algiers*. Spatial inferences of this type are thought to rely on spatial mental models that are integrated and spatio-analogical (see Section 1.1.1.) representations of the spatial relations between different objects (Johnson-Laird & Byrne, 1991), although they are normally not assumed to preserve all metric information (Tversky, 1993). Spatial mental models are integrated in the sense that objects and their relations that belong to the same state of affairs are represented in a single mental model. For example, the relation between Paris and Algiers and the relation between London and Paris would be represented together in the same spatial mental model. Furthermore, each spatial mental model represents only one possible situation (Johnson-Laird, 1999). If the known information is consistent with several different spatial situations, representing these different situations would require different spatial mental models.

Evidence in support of using mental models to draw spatial inferences is observed in preferences for certain models when available spatial information does not allow an unambiguous inference. If, for instance, you know that *London* is north of *Paris* and that *Paris* is west of *Prague,* in principle, depending on the distances between *London, Paris,* and *Prague*, the relation between *London* and *Prague* can be anything from west to north. However, when asked to report this relation, participants are quite happy to commit to a relation, even though it cannot be determined from the information in the problem (and hence is ambiguous; see Rauh et al., 2005; Jahn, Johnson-Laird, & Knauff, 2005). Moreover, the chosen relation is quite stable both within an individual and across different individuals. Accordingly, the mental model containing this preferred relation has been termed *preferred mental model*.

Section 2.5. Employing External Visualizations

Performance in the basic spatial tasks described so far can profit from employing external visualizations such as sketches, maps, or diagrams. For instance, navigation in an unfamiliar environment can be assisted by the use of a map. Moreover, external visualizations are also used in non-spatial domains to convey complex relationships and mechanisms (e.g., the workings of a combustion engine). One reason for the advantage provided by external visualizations is that their properties beneficially complement the properties of internal mental representations (Tversky, 2005). Whereas mental representations may suffer from memory capacity restrictions, visualizations are, in principle, free of this flaw. On the other hand, internal representations allow manipulating (e.g., mentally rotating, Section 1.2.1.) parts of an overall representation without manipulating the overall representation. This is normally impossible with external visualizations, as, for instance, you can only rotate the whole map and not just a single street. Thus, internal representations and external visualizations together provide a more flexible and powerful means to reason about spatial (and other types of) knowledge than a reliance on either individually. In some sense, employing external visualizations is a spatial task itself, because usually the spatial relations between elements within the external visualizations represent relations among elements in the world. For example, larger distances between boxes in a flow diagram typically indicate more intervening steps between the processes represented by the boxes. Accordingly, elements and the spatial relations between them have to be created / interpreted when producing / comprehending external visualizations.

With respect to production, Tversky (1999) suggests that the creation of a visualization reflects the organization and structure of the mental representation from which the information is drawn. If your representation of the layout of your house is hierarchical (Section 1.1.1.), it is more likely that you will produce a visualization of one of the floors by (1) drawing the outline of the floor, (2) drawing the outline of the rooms on this floor, and (3) drawing the (position of the) furniture inside the rooms in this order, rather than by drawing the elements in the reverse order. With respect to comprehension, Carpenter and Shah (1998) have proposed that understanding external visualizations consists of three processes. The first process recognizes visual patterns such as slopes of lines. The second process translates these visual patterns into quantitative and qualitative interpretations, such as describing a negative slope as a decreasing function. The third process relates existing interpretations to concepts associated with the visualization (e.g., relating decreasing temperature with increasing altitude).

Finally, external visualizations are often subject to schematization, in which certain details are omitted (Tversky, 2005). During production of an external visualization, schematization can occur either because the represented knowledge is missing some detail or is distorted (Section 1.1.1.) or because the producer of the visualization intentionally omits (irrelevant) detail to reduce the complexity of the visualization. For example, a map designer may only include major roads rather than side streets at certain scales. For comprehension of an external visualization, schematization is often advantageous, because too much detail would obscure the relevant information. For example, when reading a map, seeing each house on each road would make identifying the road and planning a path much more difficult.

Section 3. The broad influence of space

Spatial concepts are also thought to underlie our understanding of abstract concepts (Gattis, 2001 Lakoff & Johnson, 1980). In this section we discuss how our spatial facilities impact how we process, understand, represent, and reason about abstract concepts.

Section 3.1. Spatial Compatibility Effects

Imagine viewing a display that consists of single numbers that can occur anywhere on the screen, with your task being simply to indicate with one button (held in your right hand) when a number appears on the right side of the screen and another button (held in your left hand) when a number appears on the left side of the screen. When there is a spatial correspondence between the location of the number and the hand making the responses, responses are facilitated (Fitts & Seeger, 1953). This has been referred to as a spatial compability effect. This may not be particularly surprising because the judgment is a left/right judgment and it is made with left/right hands. However, imagine now that the task is to determine whether the number is odd or even, and the odd button is held in your left hand and the even button is held in your right hand. The number may appear to the left or right side of the screen but this is irrelevant to your judgment of whether it is odd or even. Nevertheless, when an odd number appears on the right (and the odd button is in your right hand) you make your response faster than when the odd number appears on the left. Similarly, when an even number appears on the left (and the even button is in your left hand) you make your response faster than when the even number appears on the right. This type of spatial compatibility effect that occurs when the spatial location of the stimulus is irrelevant to the task has been termed Simon effect (Simon & Rudell, 1967;Wallace, 1971; Hedge & Marsh, 1975, Proctor & Vu, 2002; Memelink & Hommel, 2005), and indicates that spatial location is ubiquitously processed even when irrelevant, attesting to its primary importance.

Section 3.2. Spatial Grounding of Abstract Concepts

Lakoff and Johnson (1980) argue that humans establish the meaning of abstract concepts such as love, thought, happiness, time, (social) status, etc. by basing them on directly perceivable physical reality: Abstract concepts are grounded in physical reality. One source of support for the significance of space in grounding concepts comes from language. For example, the concept of happiness is grounded in the spatial dimension of up and down. If you are feeling happy you may say “I’m feeling up” or “I’m in high spirits”. If you are sad, you may say “I’m feeling down” or “I’m depressed”. Similarly, if you state that you are “in love” or “in the middle of something” you allude to the spatial concept of containment. Such linguistic evidence is complemented by experimental work indicating, among others, that numbers are represented along a mental numberline, and that representation of time is grounded in space, as discussed next.

Section 3.2.1 The Mental Numberline

Our understanding of numbers is grounded in spatial representations. One can represent magnitude through spatial concepts like quantity (2 piles of items correspond to the number 2) or length (smaller rods correspond to lower numbers than longer rods) or by ordering numbers along a mental numberline, with low numbers anchored at one end and increasing as one moves to the other end. In support of this idea, Moyer and Landauer (1967) found that the difficulty of judging which of two numerals was larger was proportional to the difference of the magnitude of the two numerals: Numbers that are closer together are more difficult than numbers that are far apart, with a monotonic decrease in difficulty with an increase in distance. Further evidence for the existence of the mental numberline has arisen from research on the SNARC (Spatial-Numerical Association of Response Codes) effect (Dehaene, Bossini, & Giraux, 1993; see Wood, Willmes, Nuerk, & Fischer, 2008, for a recent review). In a typical SNARC experiment, participants judge the parity of digits that are shown in the center of a screen, and make an odd or even response by pressing either a left or a right response button. The SNARC effect consists of the observation that left button responses are faster for lower digits than for higher digits, and that right button responses are faster for higher digits than for lower digits. If lower numbers were consistently presented in the left half of the screen and higher numbers were presented in the right half of the screen, such an effect would be expected due to spatial compatibility and the Simon effect (Section 3.1.). However, in the basic SNARC setup, the numbers are presented in the center of the screen. That a spatial compatibility effect is nevertheless observed suggests that the conceptualization and representation of digits is inherently spatial, aligned along a mental numberline. Additional evidence for a mental numberline comes from neuropsychological investigations. Hemineglect (see Section 4.1.) patients have been reported not only to neglect a portion of perceived space, but also to exhibit difficulties representing numbers that would be located on the corresponding side of the mental numberline (Zorzi, Priftis, & Umilta, 2002).

Section 3.2.2 Time

Time can be also grounded in space. For instance, Boroditsky (2000) showed that a previously employed spatial frame of reference (see Section 1.1.2) primes temporal information processing. Participants first had to verify four sentence/picture pairs, making a judgment about the spatial relation between the depicted objects. The sentences defined the spatial relation with respect to an egocentric frame (e.g., The object is in front of me), or with respect to an object-centered frame (e.g., Object 1 is in front of Object 2). After completing the four spatial verification trials, participants were presented with an ambiguous temporal sentence such as “Next Wednesday’s meeting has been moved forward two days.” Their task was to indicate the new day of the meeting. Interestingly, participants for whom the spatial relation was defined in an egocentric frame assumed the meeting had been shifted to Friday (forward two days), whereas participants for whom the spatial relation was defined in an object-centered frame assumed the meeting had been rescheduled to Monday (back two days). These results suggest that the understanding of temporal concepts can be grounded in two different spatial metaphors. In the first metaphor the passing of time is understood by analogy to forward movement of oneself through space. If this metaphor is adopted a forward shift of a meeting indicates that the meeting will take place on a later day. In the second metaphor the passing of time is understood by analogy to an entity moving past the unmoving self that results in one being behind the moving entity. If this metaphor is adopted a forward shift of a meeting indicates that the meeting will take place on an earlier day.

Section 3.3. Reasoning by Spatial Analogies

As in the spatial domain (see Section 2.4.), new knowledge about abstract concepts can be inferred from existing knowledge. For example, knowledge about the average temperature for different altitudes can be used to infer the rate of temperature change with increasing / decreasing altitude. Such inferences over abstract domains may be realized and facilitated by drawing on abilities for spatial reasoning (Gattis, 2001). A crucial prerequisite is establishing an appropriate analogy between the abstract and the spatial domain, such that results obtained by spatial reasoning can be transferred to the abstract domain. An important and powerful mechanism by which the analogy can be established is structure-mapping (Gentner, 1983). Structure-mapping, in general, establishes an analogy between two domains by mapping elements, relations between elements, and relations between relations in the different domains onto each other. In the analogy “The atom is like the solar system”, for instance, the electrons are mapped onto the planets and the relations between the atomic core and the electrons are mapped onto the relations between the sun and the planets. Gattis (2004) has shown that structure-mapping is also central when employing spatial analogies to infer new knowledge about abstract concepts. For example, to infer the rate of temperature change with altitude, one may visualize the known temperatures for the different altitudes using two orthogonal axes by mapping altitude onto one axis and mapping temperature onto the other axis. Such mapping of altitude and temperature onto the axes implicitly also maps the rate of temperature change onto the steepness of the curve that connects all the known altitude-temperature combinations. Accordingly, the rate of change can be inferred by determining the steepness of the curve. Spatial analogies often help to make explicit some abstract relations that may be difficulty to compute otherwise.

Section 4. Neural Systems, Variation, and Learning

In this section we discuss how spatial information is represented and processed in the brain, identify possible individual differences, and discuss training and learning in spatial reasoning.

Section 4.1 Space in the Brain

Neuroscientific research is beginning to uncover where and how spatial information is maintained and transformed in the brain. At a low level, spatial information obtained by vision is represented in the primary visual cortex (V1) in the occipital lobe. Viewing objects that are close together excites neurons that are close together in V1, suggesting that the spatial layout in the world is partially mapped to the primary visual cortex. Information present in V1 is further processed in two main pathways in the brain called the ventral and dorsal pathways (Ungerleider & Mishkin, 1982). The ventral pathway extends to regions in the temporal lobe and processes non-spatial object information such as color and shape. The dorsal pathway extends to regions in the parietal lobe and processes spatial information such as the location of objects.

The parietal lobe receives and integrates spatial information across the senses (Byrne, Becker, & Burgess 2007), with structures that are thought to be responsible for mapping together different spatial reference frames (Section 1.1.2.). This is necessary because the space around the human body is represented in many different frames. For example, a reference frame that may be employed in vision may be centered on the head whereas a reference frame employed for grasping may be centered on the hand. As a result, the same location in space (e.g., a cup of coffee on your desk) may be coded in two different frames. A further central function supported by areas in the parietal lobe is directing attention to different regions of space. The importance of this function becomes most clear when it breaks down, for example, due to lesions in the parietal lobe which often results in hemineglect, a reduced awareness for one side of peripersonal space. Finally, the parietal lobe serves as a gateway for sensory information to brain structures in the medial temporal lobe such as the hippocampus and entorhinal cortext that are also involved in processing and representing spatial information.

The hippocampus and the entorhinal cortex contain neurons that represent information about one’s own location and direction in the environment (Moser, Kropff, & Moser, 2008). Neurons in the hippocampus, called *place cells*, respond selectively to circumscribed regions in the environment: A given place cell only fires when there is stimulation at the location coded by that cell. Different place cells code different places, such that the response of several place cells together allows a fairly precise localization. Similarly, neurons in the entorhinal cortex, called *grid cells*, respond selectively to particular locations in the environment. Grid cells respond to several places, with these places arranged like a grid across the environment. In contrast to earlier processing stages such as V1, the spatial representation in place cells and grid cells is not topographic. Neighboring place and grid cells may represent places that are not adjacent in the environment. A further type of neurons in the entorhinal cortex, called *head direction cells,* complements the location information given in the place and grid cells. Whereas place and grid cells code the current location largely independently from current orientation, head direction cells code the current orientation largely independently from the current location. Thus, the neurons in the hippocampus and the entorhinal cortex provide enough information to determine one’s location and orientation in the environment.

Section 4.2. Individual Differences

Different people can vary in spatial reasoning ability, such as the person who gets easily lost in a new environment and the person who can easily find their way when they encounter a detour. Several tests have been developed to assess these individual differences (Hegarty & Waller, 2005), including assessments of mental rotation ability, of the ability to imagine folding a paper in accordance with instructions, and the ability to decide when to start the movement of one object such that it intersects with another already moving object. These types of tests have revealed consistent individual differences, with some of these differences correlating with gender (Halpern & Collaer, 2005). For example, some studies have shown that men perform better than women on mental rotation (Section 1.2.1). There are also differences in giving directions (Section 2.2.) and in navigation (Section 2.1.), with women relying more on landmarks, and men relying more on directions and distances. Whereas men are normally more likely to employ cardinal directions such as east and south when giving directions, females are more likely to refer to landmarks along a route. Furthermore, women are, on average, slower and more error prone than men in navigating virtual environment mazes which in part may arise from the fact that such mazes tend to be comparatively sparse in landmarks. This may suggest that strategy differences underlie these observed gender effects (Lawton, 1996).

Section 4.3. STEM Education and Spatial Skills

Spatial reasoning is important for a number of professions and proficiencies. For example, chemists and biologists may need to understand the spatial layout of chemical compounds and molecules. Similarly, physicists and engineers work on the spatial layout of electrical circuits and mechanical devices. Geoscientists employ spatial transformations when trying to determine the events that led to the current features of a given outcrop. Indeed, Shea, Lubinski, and

Benbow (2001) suggest that spatial ability is a good predictor of success in STEM disciplines. They measured spatial ability in a large sample of 13 year olds and monitored their educational and occupational careers over the next 20 years. One main result was the correlation between spatial ability and involvement a STEM fields: Participants with higher spatial ability at age 13 were more likely to graduate and work in one of the STEM fields than people with lower spatial ability. This relationship between spatial ability and the STEM fields suggests the possibility that involvement and performance in STEM disciplines may be increased by training spatial ability (Baenninger & Newcombe, 1989).

Section 5. Future Directions

In this section, we outline five future directions for further research. First, we encourage research on the nature of spatial representations: How are representations that code different types of spatial knowledge integrated? Second, we encourage research on how spatial knowledge from long-term and working memory combines to support spatial task performance. Third, we encourage research on the differential role of egocentric and allocentric reference frames in navigation: How does the use of these frames depend on existing knowledge, task properties, and previous experience, for example? Fourth, we encourage additional research on how space can underlie non-spatial abilities such as understanding, dealing with, and reasoning about time. Lastly, we encourage research on the feasibility of training spatial abilities.

Chapters in this book that are related to spatial reasoning are: Mental Images, Spatial Attention, The Function and Architecture of Working Memory, Language and Thought, The Interplay between Movement and Cognition, The Mental Models Perspective, Analogical Reasoning, and Problem Solving.

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