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The Central Questions of Spatial Cognition

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Abstract and Keywords

Spatial cognition—how humans acquire and utilize knowledge about spatial environments—plays a significant role in everyday life. Yet many details about its underlying mechanisms remain unknown. This chapter provides an overview of the central questions in the spatial cognition literature. It focuses on four debates: the number, form, and organization of spatial representations and the mechanisms that drive spatial development. By integrating behavioral, neurological, and computational research, the authors show some of the proposed answers to these questions while clarifying the inconsistencies and limitations that can still be addressed by future research.

Keywords: spatial cognition, learning, imagery, spatial development, spatial representations

Introduction

Spatial cognition plays a significant role in everyday functioning. Consider, for example, getting ready for a day at work. Spatial cognition is involved when you brush your hair while looking at your reflection in a mirror, when you merge into traffic and navigate your way to your workplace, and when you fit your car into a parking spot. Spatial ability tests also correlate with people's self-reported performance on other common activities, including understanding graphs in magazines, packing items into a suitcase, or rearranging furniture in a room (Lunneborg & Lunneborg, 1986). These spatial activities are so tightly ingrained into our lives that it can be difficult to notice the essential role of spatial cognition in everyday activities.

Spatial cognition also has utility for specific disciplines. An architect must invoke his or her spatial knowledge when designing buildings. An engineer must understand and visualize how an object's parts move in space and interact with each other. Radiologists must understand the spatial layout of the human body to interpret x-ray images. A wide variety of military tasks, such as targeting weapons or understanding how to hide movement from enemy radar systems, require spatial cognition. Indeed, spatial ability appears to influence job success in many occupations. Ghiselli (1973) reviewed research on the relationship between spatial ability, job proficiency, and training program success and found correlations of between .18 and .28 for job performance and .35 and .46 for success in training programs. (Although these correlations are relatively low, Ghiselli concluded that they actually indicated moderate predictive validity, given that the measures were low in reliability from having been completed in real-world settings.)

The range of spatial cognition may be particularly broad because spatial ability is linked to competency in other fundamental skills that are useful for a wide range of activities. For example, spatial cognition may play a role in logical reasoning, as argued by the *theory of mental models* (Johnson-Laird, 2004). The theory states that logical processes (e.g., deduction, induction, creation) are done by constructing mental models that correspond to the situations described in logical problems. These models represent parts of the environment and the spatial relations between them, as if one were perceiving or imagining the problem’s events (Johnson-Laird, 1970). Thus, general reasoning may largely depend on the ability to generate these spatial models.

Another skill that has been studied extensively in the context of spatial ability is mathematical ability. Many studies suggest that spatial ability is strongly linked to math performance (e.g., Battista, 1990; Sherman, 1979; Smith, 1964). In a meta-analysis of 75 studies, Friedman (1995) found that correlations between spatial ability and mathematics ability were moderate at .3 to .45 (although they found higher overall correlations between spatial ability and verbal ability, $r = .4$ to .5). Spatial abilities at younger ages may also be predictive of math achievement later on. For example, Wolfgang, Stannard, and Jones (2001) followed a group of children from preschool until high school and found that students who experienced more spatial play and could skillfully build LEGOs (thought to be a heavily spatial activity) at young ages were more likely to show high mathematical achievement in middle and high school. As expected, spatial ability appears most important for the types of math that heavily involve spatial relationships, such as geometry (Stallings, 1985). That said, it is sometimes unclear whether spatial visualization uniquely contributes to math ability, or whether spatial ability effects are sometimes conflated with general intelligence effects because many studies use spatial measures that are similar to general intelligence measures and do not include a general intelligence measure for control (Chipman, 2005).

Despite spatial cognition’s importance and wide reach, there are still many basic questions left unanswered. To fully understand how spatial cognition affects our everyday lives, it is necessary to answer these questions about the characteristics of spatial representations that are used in spatial activities. In this chapter, we will first provide an overview of the components that make up spatial cognition and then delve into some specific debates regarding spatial representations' organization, form, and development.

Components of Spatial Cognition

Historically, two different research traditions have contributed to analyzing the distinguishable parts of spatial cognition. Because spatial ability has practical importance as a potential predictor of training and occupational success, tests of spatial abilities were developed quite early in the history of psychology. Neuropsychology also has a long history of contributing to our understanding of separable components of spatial ability, primarily with studies investigating the consequences of brain damage.

Many plausible measures of spatial ability have been developed, but they do not correlate perfectly with each other. Thus, a number of studies have analyzed performance on batteries of these spatial ability measures using factor analyses, a statistical technique that looks at correlations among variables to group the variables into separable components (Carroll, 1993; Lohman, 1988; McGee, 1979). There is considerable variation in the number and types of factors found by these analyses, largely arising from statistical technicalities. However, the following three factors are often agreed upon: spatial visualization, spatial orientation, and spatial relations. *Spatial visualization* refers to the ability to encode and mentally manipulate spatial objects. The tests that measure this factor are relatively complex, involving multistep problems (e.g., the Cube Comparison Test, in which the participant must decide if two three-dimensional cubes with letters on their faces are the same or not when rotated). *Spatial orientation* is the ability to reason about spatial relations relative to the observer's (either the participant or a hypothesized observer) perspective, although Carroll (1993) argued that this factor was not separable from spatial visualization, and other studies have found a high correlation between the factors of orientation and visualization (e.g., Borich & Bauman, 1972; Vincent & Allmandinger, 1971). *Spatial relations* is the ability to rotate simple, two-dimensional objects.

Evidence suggests that the spatial visualization component may be particularly important for other domains (e.g., Fennema & Sherman, 1977), possibly because visualization ability level determines the types of spatial representations that are available to an individual for problem-solving. For example, many researchers have drawn a distinction between visualizer and verbalizer cognitive styles (e.g., Hegarty & Kozhevnikov, 1999;

Lean & Clements, 1981): *visualizers* are more likely to use visual spatial representations to solve problems, whereas *verbalizers* are more likely to use verbal analytical methods. Within visualizers, those with high spatial ability are more likely to construct schematic spatial representations that depict the spatial relations described in a problem (which are also associated with higher problem-solving success), whereas low spatial ability visualizers are more likely to construct pictorial representations that depict the objects described in a problem rather than their relations (Hegarty & Kozhevnikov, 1999; Kozhevnikov, Hegarty, & Mayer, 2002). Furthermore, when presented with graphs of motion (showing position, velocity, or acceleration of objects over time), those high in spatial visualization abilities were able to accurately interpret the abstract relations shown in the graph whereas those low in spatial visualization ability were not, suggesting that spatial visualization ability influences both the creation and interpretation of spatial representations. However, overreliance on spatial strategies can sometimes hinder students; for example, Lean and Clements (1981) found that students who preferred verbal strategies on math problems outperformed students who preferred spatial or visual strategies, although they did not analyze their results based on the types of problems in their math test.

The factor analysis literature has its limitations. For one, the results of the analyses depend on the tests that are used: a factor will only be found if enough of the included tests measure that factor. In addition, many early factor studies used exploratory factor analysis methods out of necessity, defining factors post-hoc rather than testing hypotheses about which factors might exist since potential factors had not been identified yet by prior research. Still more recent studies using confirmatory factor analyses, which test for hypothesized factors, support the factors found in exploratory studies. For example, Hegarty and Waller (2004) asked participants to take tests meant to measure spatial visualization and orientation and then explicitly tested a one-factor model, in which all tests would load onto a unitary "spatial ability," against a two-factor model, in which tests would load separately onto a spatial visualization factor and a spatial orientation factor. The two-factor model provided the better fit to the data, consistent with evidence for separate spatial components.

Factor analyses also assume that all participants are using the same strategy on a given measure, but many studies have found this to be untrue (e.g., Carroll, 1993). Often, tests allow more than one strategy, and different versions of a test or even different items on the same test can encourage certain strategies (Just & Carpenter, 1985). The ability to flexibly switch between strategies is also thought to set experts apart from novices in spatial domains (Hegarty, 2010) because novices are likely unable to consciously choose the strategies they use for a given task. After the rise of cognitive psychology, in the 1980s, a number of researchers began to investigate the cognitive processes used in responding to spatial ability test items. For example, Just and Carpenter (1985) investigated how people with low spatial ability and those with high spatial ability differ on a common spatial test, the Cube Comparison Test (described earlier), which is thought to involve three-dimensional mental rotation. Through verbal protocols, they discovered that people with low spatial ability tend to rotate around axes that line up with the shown cube. In contrast, people with high spatial ability do not restrict themselves to these same axes. Low spatial ability participants took longer to perform the initial rotation of the cube and to confirm whether the two cubes matched after rotation. Because factor analyses cannot guarantee that participants use specific strategies on a given test, this may affect how cleanly measures load onto individual factors.

The commonly found separation between spatial visualization and orientation hints at a distinction between different scales of environment. Spatial visualization tasks generally require spatial manipulation at a small scale, whereas orientation tasks often require the observer to imagine herself within a larger environment. Many studies support this scale dissociation (e.g., Huttenlocher & Presson, 1973, 1979; Kozhevnikov & Hegarty, 2001; Pearson & Ialongo, 1986), and a review of 12 studies by Hegarty and Waller (2005) found mostly weak ($r < .3$) or nonsignificant correlations between small-scale and large-scale abilities. The neuropsychology research provided complementary evidence that the two environmental scales utilize different brain regions: patients with parietal damage show impaired small-scale spatial abilities and intact large-scale abilities (Philbeck, Behrmann, Black, & Ebert, 2000), whereas patients with impaired large-scale abilities show intact small-scale abilities (Aguirre & D’Esposito, 1999). Following this, many models of space distinguish between “near” or “manipulative” spaces, which include the space near the body in which objects can be manipulated and the space that can be seen from a single vantage point, and “far” or “navigable” space, which includes the space that cannot be viewed from a single point (e.g., Cutting & Vishton, 1995; Harrison & Schunn, 2003; Previc, 1998; Tversky, 2003; see the “Organizing Multiple Representations of Space” section for more details). However, other studies have found shared variance between small-scale performance and large-scale performance (e.g., Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006), so small- and large-scale spaces may still share common processes that work together to accomplish more complex spatial tasks.

For *small-scale spaces*, one class of theories suggests that spatial representations store spatial relations in a quasi-pictorial format, such that spatial relations are built into the representation (Kosslyn, 1980, 1994; Kosslyn, Thompson, & Ganis, 2006). Others argue that these spatial representations do not have built-in spatial relations but are instead made up of symbolic propositions that can describe these relations (Pylyshyn, 1973, 1981, 2002). These two theories and the debate between their proponents are described in more detail in the “What Form Do Representations Take?” section.

In studies of *large-scale spaces*, research distinguishes three types of spatial information: landmark knowledge, route knowledge, and survey knowledge. *Landmarks* are defined as unique objects in space that are fixed in location (e.g., buildings or monuments). *Route knowledge* consists of sequences of locations that are experienced when one travels and is typically used when traveling a familiar route. *Survey knowledge* is spatial information that is abstracted and integrated from different routes of the same space to create a unified model of that space, a "cognitive map" thought to act similarly to a physical bird's-eye map of an environment (Tolman, 1948); this information may be employed when trying to find novel routes through a familiar space (e.g., shortcuts or detours).

An early theory was that information about an environment was acquired starting with landmark knowledge, then route knowledge, and finally survey knowledge (Siegel & White, 1975). A person would first acquire information about the unique features identifying a location (in the form of landmarks), then acquire route knowledge by traveling routes that connected landmarks together, and then develop a survey representation that included the interrelations of these routes and landmarks. To illustrate this process, Kuipers (1978) created a computational model (called the TOUR model) that could form a cognitive map of an urban environment through route knowledge by taking simulated observations of routes as input and then adding these observations into a cognitive map. The model showed that it was possible to derive survey information using route information as the primary source of input. However, other studies have shown that landmark, route, and survey information can be acquired simultaneously (e.g., Hirtle & Hudson, 1991; Thorndyke & Hayes-Roth, 1982) and that humans may not be able to readily glean information for a cognitive map from route knowledge under typical navigational circumstances (e.g., Freundschuh, 1991; Golledge, Gale, Pellegrino, & Doherty, 1992; Lloyd, 1989).

Despite drawing analogy to external maps, cognitive maps are not *equivalent* to physical maps. Unlike physical maps, cognitive maps are not necessarily a unitary representation and may consist of discrete knowledge pieces stored in memory (e.g., knowledge of individual landmarks, route segments, or regions of a space). They are also not necessarily pictorial (see the "What Form Do Representations Take?" section). Additionally, cognitive maps are prone to systematic biases (e.g., Hirtle & Jonides, 1985; Moar & Bower, 1983; Stevens & Coupe, 1978) that are likely caused by the hierarchical structure of cognitive maps.

In this hierarchical structure, different regions of an environment are stored at different levels, with more detailed spatial knowledge available to lower levels of the hierarchy, while higher levels represent more general spatial relations. Strong hierarchical theories suggest that spatial relations across different hierarchical levels are not encoded into memory; instead, such spatial relations are thought to be only inferable from higher levels of knowledge. This structure leads to a low storage resource cost but requires more computation during spatial processing. In contrast, partial hierarchical theories state that spatial relations at different hierarchical levels can be encoded into memory, even though they can also be inferred from higher level relations. This redundancy comes at a higher storage cost but has lower immediate computational requirements. Work by McNamara (1986) showed that people are faster at judging distances within the same hierarchical level but are also affected by spatial relations across hierarchical levels, consistent with a partial hierarchical structure.

A well-known example of the biases caused by hierarchical structures comes from Stevens and Coupe (1978), who asked participants about the directional relationship between Reno, Nevada, and San Diego, California. Most participants responded that Reno is east of San Diego, even though Reno is actually to the northwest. The authors suggested that this is because participants have only encoded information about the spatial relation between Nevada and California (in which Nevada is east of California), a superordinate level of the hierarchy, rather than the lower level of individual cities (see Figure 1). Stevens and Coupe also found similar biases for other geographic locations (e.g., the relation between the Atlantic and Pacific entrance of the Panama Canal).

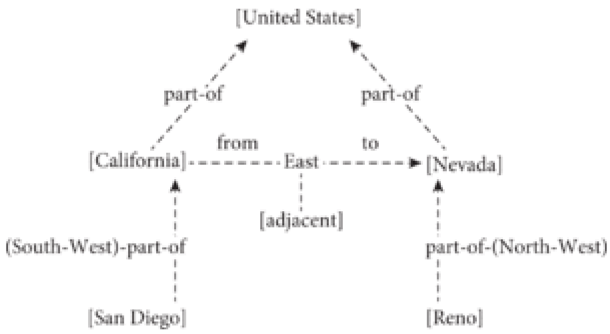

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Figure 1. An example of a partial hierarchical representation showing the relation between San Diego and Reno. Dotted lines signify relationships encoded into memory. In a strong hierarchical representation, there would be no lines linking California to Nevada.

From McNamara (1986).

Another important distinction in large-scale maps involves the frame of reference of route and survey knowledge. Route knowledge is thought to take an egocentric frame of reference, in which spatial relations are encoded with respect to the viewer (e.g., the car is to the right of an individual). In contrast, survey knowledge is thought to take an allocentric frame of reference, in which spatial relations are encoded in relation to external objects in space, not relative to the viewer (e.g., the car is north of the fire hydrant). This egocentric–allocentric split appears to be reflected in brain regions (e.g., Committeri et al., 2004; Hartley, Maguire, Spiers, & Burgess, 2003). Evidence for egocentric representations have been found at the level of single neurons in the sensory and motor cortices in primates; neurons in these regions respond to visual stimuli at specific retinotopic locations, but their firing rate is modulated by the orientation of the monkey's gaze relative to its head (Andersen, Essick, & Siegel, 1987), by the orientation of the head relative to the trunk, and by the orientation of the monkey within the testing room (Snyder, Grieve, Brotchie, & Andersen, 1998). The existence of such cells suggests that the animal's perspectives in space are represented.

For allocentric representations, location-selective "place cells" have been found in the rat hippocampus (and other extra-hippocampal regions, e.g., Jung & McNaughton, 1993; Quirk, Muller, Kubie, & Ranck, 1992) that represent the location of the rat relative to the surrounding environment (O'Keefe, 1976; O'Keefe & Dostrovsky, 1971). Furthermore, the entorhinal cortex, a major input to the hippocampus, contains "grid cells" that similarly fire at specific locations in an environment (Fyhn, Molden, Menno, Moser, & Moser, 2004; Hafting, Fyhn, Molden, Moser, & Moser, 2005). These grid cells fire at equal distances in a grid shape, so it is likely that grid cells provide metric measures to cognitive maps. Although most classic studies on place cells and grid cells have involved rats, humans appear to have similar coding mechanisms in both the hippocampus (Ekstrom et al., 2003) and in the entorhinal cortex (Doeller, Barry, & Burgess, 2010; Jacobs et al., 2013).

However, a computational model by Harrison and Schunn (2002, 2003) suggests that the egocentric–allocentric split may be faulty and that navigational methods relying on allocentric maps are computationally taxing and unsupported by existing data (see the "Organizing Multiple Representations of Space" section for more detail). Instead, they propose three spatial systems, one of which is directly relevant to the navigable space: the *configural system*, a memory system that relies on egocentric vectors for navigating space. This system represents objects in space as things around which to be navigated. As the navigator moves through space, the locations of objects are updated through path integration. As both a memory and a spatial system, if located in the hippocampus or parahippocampal regions, then the configural system could explain why the hippocampus is associated with both memory and navigational functions. Wang and Spelke (2002) also proposed a model of spatial memory that depended only on egocentric properties (namely, view-dependent scene recognition and spatial updating of egocentric locations using self-motion information) and a geometric module, which represented the surface geometry of the surrounding environment. However, other models have been proposed in which egocentric and allocentric representations can exist in parallel. For example, Burgess (2006, 2008) suggested a model in which egocentric representations are provided by the parietal lobe, allocentric representations are provided by the hippocampus and medial temporal lobe, and the retrosplenial cortex and parieto-occipital sulcus facilitates translations and interactions between the two types of representations.

Regardless of the exact details of the large-scale spatial representations, it is clear that the typical person has access to a number of different large-scale spatial representations. Empirical evidence suggests that these multiple representations of the same space can exist simultaneously, with people using representations strategically depending on the task and its demands (e.g., Bridgeman, Peery, & Anand, 1997; Shelton & McNamara, 1997). For example, Brockmole and Wang (2002) gave people directions to target objects and asked them to judge whether the given direction was correct or not. Some objects were from a familiar environment, whereas others were from an unfamiliar environment; consequently, some trials took place after a “switch” in environments (e.g., the previous trial involved the familiar environment while the current trial involved the unfamiliar environment, or vice versa). It took significantly longer for participants to judge directions after a switch than when no switch was required, suggesting that participants were utilizing one of two different representations of space during the task depending on the initial input, rather than one larger unified representation.

Given that multiple representations of space can coincide to hold the different components of spatial cognition, humans must have some meaningful way of organizing objective space into separate mental representations. The next section discusses the different types of organizational models that have been used to categorize spatial representations.

Organizing Multiple Representations of Space

Many models have been proposed to describe how perceived space is partitioned, with each space corresponding to its own representations. Although most models share some similarities in the general spaces that they represent, the details of the models’ spaces vary. Some models separate spaces based on their functional significance (e.g., Cutting & Vishton, 1995; Tversky, 2003). Other models separate spaces based on neuropsychological distinctions (e.g., Previc, 1998; Rizzolatti, Gentilucci, & Matelli, 1985). Finally, others separate spaces based on computational considerations (e.g., Harrison & Schunn, 2002, 2003). We discuss several prominent models in more detail below.

Functional Models of Space

Functional models base spaces on the patterns of behaviors and cognitions that take place within the space. A notable example of a functional model is Tversky's model of space (2003), which considered four functional spaces: the space of the body, the space around the body, the space of navigation, and the space of external representations.

The *space of the body* is the space in which we directly perceive and experience the world. People experience space both within and outside of the body: they plan their body's actions and also experience sensory feedback based on the consequences of their body's movements. The body can also be perceived as an object in space, although it is unique because it is being simultaneously experienced from inside. This unique experience causes people to represent the body in different ways from external objects (Chatterjee, Freyd, & Shiffrar, 1996).

The *space around the body* is the space that can be seen from a person's current position. Here, a person learns about and acts on the world. Franklin and Tversky (1990) suggest that this space is mentally conceived of in terms of three body axes: head/feet, front/back, and left/right. Objects in the space are then attached to these axes. Many studies have found that information about objects is more quickly retrieved when these objects are on the head/feet axis or the front/back axis, compared to the left/right axis (e.g., Bryant, Tversky, & Franklin, 1992; Franklin & Tversky, 1990; Newcombe & Huttenlocher, 1992). Franklin and Tversky (1990) argue that this is because the head/feet axis and front/back axis are both asymmetric in relation to the world and body, whereas the left/right axis has no obvious asymmetry.

The *space of navigation* involves the space that we move through while traveling. Objects within this space include specific locations (such as buildings or landmarks) and large-scale objects that cannot be directly manipulated (such as countries). Because this space is so large, it is impossible to perceive the entirety of the space at once. Instead, to consider the space as a whole, a mental map of the space must be constructed from various pieces of information about the different parts of the space. These pieces must then be integrated within the mind, which is an impressive endeavor because the spatial information can be acquired in different forms (such as from maps or from personally exploring the space), in different scales, and from different viewpoints. Tversky (2005) suggests that this disjointed information can be approximately combined using shared reference objects or reference frames, which leads to systematic errors during retrieval.

A unique space is the *space of external representations*, or the space involved when we use external tools, such as maps or diagrams, to think about space. Unlike the other spaces in Tversky's model, it is not naturally present in the world; rather, it is a human-constructed space. The external tools that exist within this space can represent both literal spatial relations that exist in the world, such as those depicted by maps, or metaphorical spatial relations, such as those depicted by the arrows and links in diagrams. The spatial relations illustrated in external tools usually correspond to actual spatial relations that exist in the world.

Neuropsychological Models of Space

Ungerleider and Mishkin (1982) were among the first to connect anatomical distinctions within the brain to spatial activities. Their model divided the brain along two anatomical streams that projected from the primary visual cortex. The dorsal ("*where*") pathway, which connected the occipital cortex to the posterior parietal cortex, subserved spatial localization. The ventral ("*what*") pathway, which connected the occipital cortex to the inferotemporal cortex, subserved pattern recognition.

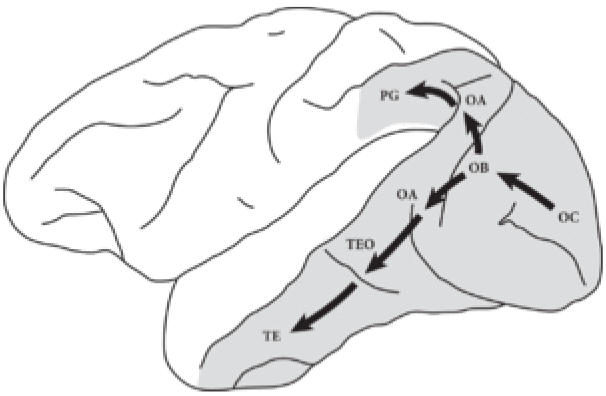

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Figure 2. Schematic of the dorsal (spatial) and ventral (object) cortical visual pathways shown on the rhesus monkey's left hemisphere.

From Mishkin, Ungerleider, and Macko (1983).

Bear (1983) expanded on Ungerleider and Mishkin's model by including two new pathways: a parietal-frontal system extended the dorsal pathway, while a temporal-frontal system extended the ventral pathway (see Figure 2). The parietal-frontal system went through the inferior parietal lobe to the cingulate gyrus to the dorsolateral frontal cortex and was said to be involved in spatial surveillance and spatial orientation. The temporal-frontal system went through the temporal visual pathways to limbic areas (including the hippocampus and the amygdala) to the orbitofrontal cortex and was said to be involved in storing visuoemotional associations.

More recently, Milner and Goodale (1998) revised Ungerleider and Mishkin's model to focus on the different ways that visual information is transformed for output purposes. Instead of a dorsal "where" and a ventral "what" stream, they instead proposed a dorsal "*how*" and a ventral "*what*" stream. In this revised model, the dorsal stream transforms visual information using an egocentric frame of reference to prepare actions. The ventral stream processes object features using various frames of reference to create object representations.

Previc (1998) attempted to use the dorsal/ventral distinction to frame different realms of space, theorizing that the dorsal and ventral pathways would be biased toward different visual fields and spaces. Previc posited four spaces: the peripersonal space, the focal extrapersonal space, the action extrapersonal space, and the ambient extrapersonal space. Each space involves differential degrees of emphasis toward upper and lower visual fields, different functional properties in space, and different anatomical localizations within the brain. Note that Previc’s model is quite similar to Tversky’s.

The *peripersonal space* involves visuomotor operations in the near-body space, for functions such as visual grasping and manipulation. The space exists approximately 0 to 2 meters from the body, in a 60-degree arc in front of the body, with a bias toward the lower visual field. It appears to generally use a body-centered, egocentric reference frame (Previc, 1990). It is anatomically localized in the dorsolateral cortex.

The *focal extrapersonal space* is involved in visual search, object recognition, and face recognition. It is located in the space 0.2 meters and farther from the body, in a 25-degree arc in front of the body, with a bias toward the upper visual field. The space uses egocentric coordinates that are most likely retinotopic (Deneve & Pouget, 1998; Farah & Buxbaum, 1997), and it is primarily localized in the ventrolateral cortex.

The *action extrapersonal space* is involved in navigation (in relation to objects and topographically defined space), scene memory, and target orientation. It is the space 2 meters and farther from the body, located completely around the person (although there is compression outside of 200 degrees from the front of the body), with a bias toward the upper visual field. The space primarily uses gaze-centered, egocentric coordinates (Bisiach & Luzzatti, 1978; Rolls & O’Mara, 1995). It is localized in the ventromedial cortex of the brain.

The *ambient extrapersonal space* is involved in spatial orientation, postural control during movement, and stabilizing the perception of the world during movement. The space is the area more than 2 meters away from the body, in a 180-degree arc in front of the body, with a bias toward the lower visual field. The space generally uses exocentric coordinates, often using gravity and the earth as a frame of reference (Angelaki & Hess, 1995). The ambient extrapersonal space is primarily represented in the dorsomedial cortex.

Computational Models of Space

Computational evidence has suggested that models of space that separate egocentric and exocentric maps may be inaccurate. After reviewing the literature on place cells and spatial view cells, Harrison and Schunn (2003) concluded that navigational methods that rely on exocentric maps are both computationally taxing and unsupported by existing data. Instead, the authors (2002) proposed the Adaptive Control of Thought–Rational/Spatial (ACT-R/S) model of space, a spatial processing elaboration of the ACT-R general cognitive architecture (Anderson & Lebiere, 1998). The model relies on three visuospatial systems—the visual system, the manipulative system, and the configural system—that are behaviorally and neurologically separate.

The *visual system* is primarily used to identify objects based on their perceptual details. Extensive spatial information is not necessary for the system to function, and the system can still recognize objects using simple, two-dimensional retinotopic information. It is anatomically based in primary visual areas and ventral visual processing areas.

The *manipulative system* is used for representing objects for manual manipulation. Thus, the system deals only with three-dimensional representations of objects involving parts of larger objects characterized by simplified geometrical shapes (e.g., cylinders, cones, spheres; Biederman, 1987). The formed representations are then communicated to the motor system to help plan motor movements. The system is localized in the dorsolateral visual stream and the parietal cortex.

The *configural system* is a memory system used to represent objects in space as things around which to be navigated. It relies entirely on egocentric vectors, such that objects are located relative to the self and dynamically updated through path integration as the navigator moves through a space.

The ACT-R/S model has successfully simulated spatial behavior. Hiatt, Trafton, Harrison, and Schultz (2004) programmed a robot to follow the ACT-R/S model, such that all movements were performed by mentally transforming only the configural buffer's contents by a vector; thus, only the robot's mental location and perspective changed. With this model, the robot was able to use spatial references in a speaker's language (e.g., "to my left") to search for objects by taking the speaker's perspective. It could also use perspective cues to clarify ambiguous instructions from the speaker. For example, if the speaker asked the robot for "the wrench" when there were two wrenches available, the robot was able to take the speaker's perspective, identify which of the two wrenches was visible from the speaker's position, and use that information to determine the wrench referred to by the speaker.

In sum, a number of organizational models provide information about how spatial representations are categorized that consider functional, neuropsychological, and computational issues. However, they largely ignore another central question: what form do these representations take? Because of recoding and informational equivalence, a given type of content can be represented in a variety of forms. In the next section, we will discuss a well-known historical debate on the forms of visual-spatial representations (but note that other modalities have also been studied, e.g., Zatorre & Halpern, 2005), as well as more recent theories that have emerged on the topic.

What Form Do Representations Take? The Analog–Propositional Debate

The most prominent and competing categories of theories answering this representational format question are the analog theories and the propositional theories. *Analog theories* propose that visual mental representations are similar to visually perceived pictures, in that mental representations include intrinsic spatial properties (i.e., spatial relationships are not just described in the representation, but are also spatially depicted in the representation itself). *Propositional theories*, on the other hand, argue that visual mental representations consist primarily of formal, symbolic statements. A representation's statements can describe the spatial relations that are being represented, but the representations themselves do not have any spatial properties.

Initial evidence for analog theories came from behavioral experiments showing that mental visual representations and visual processing share many behavioral patterns. For example, Shepard and Metzler (1971) found that it takes people more time to mentally rotate objects when the angle of rotation is larger, as would be the case for physical rotation. Similarly, people take a longer time to mentally scan between features in a mental image when those features are farther apart (e.g., Borst & Kosslyn, 2008; Kosslyn, Ball, & Reiser, 1978; Pinker & Kosslyn, 1978). People also take more time to judge features of an imagined object when those features are small rather than large in comparison to the entire imagined object (Kosslyn, 1980). These behavioral results suggest that visual mental representations contain inherent spatial properties because they retain the same spatial behavioral patterns as actual images or objects. However, it is also more difficult to reinterpret mental images than physical pictures. For example, Chambers and Reisberg (1985) showed participants ambiguous pictures for a short duration, so that participants could only see one interpretation of the picture. Participants were unable to see the second interpretation of the picture from their formed mental images even when given hints or encouragement. Yet when given the chance to draw the image on paper afterward, they were able to find the second interpretation of the picture, ruling out visual complexity as the source of the problem. This suggests that, although spatial representations may hold some spatial properties, they may not be a complete analog of visual processing.

Kosslyn (1994) further elaborated on existing analog theories by identifying several retinotopically mapped brain regions, such as the primary visual cortex (V1), onto which both mental images and visually perceived images could be projected. This correspondence predicts that overlapping brain regions should support both visual perception and visual mental representations. Indeed, many studies have found that occipital regions involved in visual processing are also activated when participants mentally visualize images (e.g., Behrmann, 2000; Miyashita, 1995). The type of image being imagined also influences activation in ways that parallel visual processing. For example, when imagining detailed pictures, areas V1 and V2 are highly active, both of which are known to be spatially organized; and when the primary visual cortex is disrupted with transcranial magnetic stimulation, visual imagery is also disrupted (Kosslyn et al., 1999). Patients who have lost vision from brain damage also suffer imagery deficits (e.g., Farah, 1989; Farah, Soso, & Dasheiff, 1992). These neuroscience findings argue against propositional theories because propositional theories would suggest that nonperceptual regions of the brain should be activated during imagery instead of perceptual regions (Kosslyn, 1994).

Meanwhile, evidence for propositional theories came primarily from early artificial intelligence research that had successfully utilized symbolic systems to represent spatial structures (e.g., Baylor, 1973; Moran, 1973; Newell, 1972; H. A. Simon, 1972). For example, Moran (1973) modeled a study in which blindfolded participants were asked to imagine themselves on a two-dimensional plane. Participants were given a sequence of cardinal directions; for each direction given, the participants imagined a line drawn in that direction from their current location on the plane. They were then asked to repeat the drawn path to the experimenter. Moran’s program modeled long-term memory as symbolic condition-action rules and short-term memory as a constantly updating list of 10–20 symbolic expressions that represented any knowledge that was immediately accessible. When the program was given directions as input, it was able to output stylized verbal output to match participants’ verbalizations. This heavily spatial task could be modeled with a system using only symbolic propositions to represent spatial properties, thus showing that a propositional system for human spatial representations would be viable.

The merit of the long-standing analog versus propositional representations debate was called into question by Anderson (1978). He argued that analog and propositional theories produce identical empirical behavior, making it impossible to argue for one representational theory over the other. Instead, he claimed that the empirical evidence put forth to support either analog or propositional representations was really evidence for cognitive processes that could be associated with either representational type. Thus, it would be impossible to distinguish the internal representations posited by analog theories from those posited by propositional theories based on behavioral data alone.

However, others on both sides of the analog–propositional debate have challenged Anderson’s (1978) arguments. For example, Werner, Saade, and Luer (1998) argued that, even if analog and propositional theories lead to similar processes and behaviors, analog representations are often more parsimonious and more testable than propositional representations. Additionally, both analog and propositional theories lack specificity about key parts of their theories, leaving them open to criticism from the opposing side. In the case of analog theories, it is unclear how a mental image can contain useful properties of physical images (e.g., the spatial relations) while still remaining distinct from physical images. Some researchers have attempted to clarify these “quasi-pictures” in more detail (e.g., Tye, 1991; von Eckardt, 1988), but others argue that the concept is still too vague to be useful (e.g., Slezak, 1995; Thomas, 2009). For propositional theories, the precise format of the symbolic propositions is unspecified. Fodor (1975) argued that these descriptions were formed from an innate syntactical representational system known as “mentalese,” but there is conflicting evidence as to whether this innate system exists. Kosslyn and Pomerantz (1977) have also argued that propositional theories are too powerful because they do not define any inherent constraints and so can be fit to any experimental data by adding constraints ad-hoc as needed (e.g., constraints about how propositions are organized or how propositions are processed). Both theory types in their current states cannot fully explain all spatial representational phenomena, and, thus, the analog-propositional debate has continued.

The Dual Code and ACT-R/S Theories

As an alternative to the primary analog and propositional theories, Anderson (1978) argued for the possibility of a dual-code system. Based on Paivio’s dual-code theory (1971), this theory proposes that humans have both a verbal memory system using verbal representations and an image memory system using mental images. Anderson claimed that the arguments for a system that uses only pictorial or verbal representations were weak and that a dual-code model was viable and perhaps more plausible than a single-code theory. To illustrate a dual-code model, he gave the example of mentally representing a chess board (see Figure 3). It is possible to represent an end-game state of the board through a group of pictorial representations (which may be useful if there is a limited amount of information that can be held in one pictorial representation). Verbal propositions are also attached to the pictorial representations to provide interpretations of the image. The pictorial representations are also incomplete because they do not depict the full chessboard; instead, they represent only meaningful subunits of the full image, reflecting the way in which humans perceive images in meaningful chunks (Chase & Simon, 1973) and consistent with experimental data showing overlap between imagery and perception.

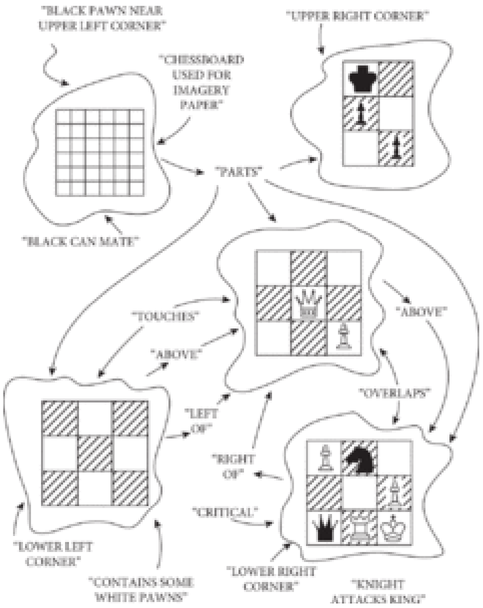

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Figure 3. A dual-code representation of a chess board.

From Anderson (1978).

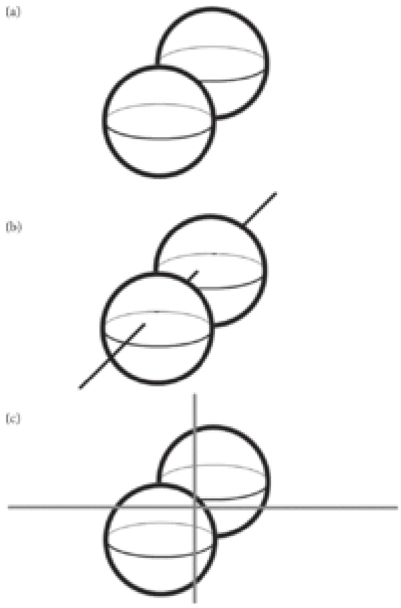
Similarly, thinking about the analog–propositional debate in terms of the ACT-R/S framework (previously described in the “Organizing Multiple Representations of Space” section) may help make sense of the experimental data that neither analog nor propositional theories alone can fully explain. ACT-R/S proposes that humans possess a visual system used for object identification, a manipulative system used for grasping and tracking objects, and a configuration system for navigation (Harrison & Schunn, 2002, 2003). It is possible that each of the systems uses a different form of representations (analog, propositional, or a combination), leading to different behavioral results depending on the task and system involved. This could explain why tasks that involve object recognition (e.g., interpreting ambiguous images) show noticeable differences between mental representations and visual perception, which is inconsistent with analog theories, whereas tasks that involve imagining the manipulation of objects or walking through an imagined space (e.g., mental rotation, mental folding, imagining traveled distances) show response time patterns that match with behavioral data and are consistent with analog theories. Additionally, the separation of systems may also explain why some experiments find overlap between perceptual and imagery brain regions while others do not if separate visuospatial regions are recruited depending on the task. Thus, a multicode system involving both pictorial and verbal representations may be more plausible than a system that involves only one representational type.

Foundational Resources and Mechanisms of Change

In the previous sections, we looked at the types of spatial representations that exist and how people organize and coordinate these different representations. It is clear that there is much that a person needs to learn to become proficient in spatial ability, which, as noted at the beginning of this chapter, can have significant impacts on everyday functioning. It is important to understand how spatial cognition develops to inform how to best teach and support the acquisition of these skills. Theories on the development of spatial cognition have revolved around two general questions: do humans possess any foundational resources for spatial cognition at birth? And, through what mechanisms does spatial cognition develop over time? Four different prominent perspectives attempt to answer these questions. We will begin by discussing the earliest perspective on spatial cognition development, by Piaget, and then review the three other perspectives that arose from challenges to Piaget's claims.

The Piagetian Perspective

The work of Jean Piaget in the 1950s and '60s initiated much of the literature on the development of spatial cognition. Piaget approached spatial development from a constructivist perspective, which claims that humans gain knowledge and create an understanding of the world through their own experiences. According to Piaget's original theorizing, infants are born as a blank slate, with no knowledge of space and no understanding that permanent objects occupy that space (Piaget & Inhelder, 1956; Piaget, Inhelder, & Szeminska, 1960). Through experience across many years, infants were thought to gradually construct more complex spatial cognition through visual and manual interactions with their physical environment. Visual salience appears to be the initial driver of these interactions, but through reaching and other experiences, infants learn to interact with more easily graspable objects (Libertus et al., 2013). Infants are thought to begin conceptualizing objects and spatial locations topologically, such that spatial relations are defined only in terms of object relations (e.g., whether objects were touching or not, or whether they were near or far from each other; see Figure 4). Once infants develop an understanding of object permanence (i.e., that an object exists even if it is not visible to the infant), they are then able to develop the ability to code locations using more complex forms of space, such as *projective space* (where the order of objects is coded along a line of projection extending from one object to another) or *Euclidean space* (where objects are coded in reference to vertical and horizontal lines). Piaget also thought that infants and children had to grow out of "spatial egocentrism," the belief that all people's visual view of the world matched their own, regardless of spatial location. Piaget claimed that children would reach an adult level of spatial understanding at around 9 or 10 years of age.



Click to view larger

Figure 4. Depiction of (a) topological space (space defined in terms of object relations), (b) projective space (space defined along lines of projection), and Euclidean space (space defined in reference to vertical and horizontal lines).

From a computational perspective, Piagetian theories and empirical descriptions provided foundational characterizations of what might be included in spatial cognition—the alternative representations of space that the mind must include. The theory also suggested that these representations could be developed though environmental input. However, Piaget did not actually provide any detailed theory of the way in which such knowledge actually could be constructed. For the case of number conservation, a related area of Piaget's investigations, the Q-Soar model (T. Simon & Klahr, 1995) demonstrates the viability of environmental experience for developing fundamental properties by simulating a child learning number conservation knowledge by experiencing conservation tasks. However, no one has yet developed a similar model for the development of spatial understanding. The computational perspective provided by Q-Soar does highlight an important weakness in the Piagetian account: it is difficult to understand how fundamental concepts of space can develop through experience without having some original concept there in the first place.

Although Piaget was able to identify many prevalent spatial phenomena, follow-up studies have revealed that infants have basic spatial competencies and that children are generally able to reason spatially at more complex levels than Piaget claimed. For example, both infants and children have shown the ability to reason about distance and spatial perspectives (e.g., Miller & Baillargeon, 1990; Newcombe, Huttenlocher, Drummey, & Wiley, 1998), which would be impossible if they were only able to code space topologically (although it has been argued that this is due to the oversimplifying of spatial tasks; see Chapman, 1988). Thus, it appears that infants are not quite blank slates, but come equipped with some capability for spatial cognition.

The Vygotskian Perspective

Similarly to the Piaget's views, the Vygotskian perspective describes spatial development from a constructivist perspective. Children begin as blank slates, and understanding is shaped through interactions with the world. However, the Vygotskian perspective focuses on the sociocultural context in which cognitive development takes place, instead of the nature of what is developing within the child. It emphasizes that cognition is situated within a social and cultural environment: human cognition has adapted to specific situations, so the application of knowledge can also be specific to situations (Rogoff & Lave, 1984). This approach provides some resolution to the fundamental computational challenge regarding the origins of fundamental spatial knowledge by proposing that this information comes from one's social and cultural environment. Although children may be limited in the amount of learning they can complete on their own, they can learn to understand more complex spatial concepts from older children and adults (also known as "guided participation"; Rogoff, 1990). Cultural tools, such as language or symbolic representations, can also shape and change children's spatial capabilities (e.g., Bowerman, 2000; Gentner & Rattermann, 1991).

Consistent with the Vygotskian theoretical framework, studies suggest that social interaction can have a significant role in spatial development. Adults are known to provide spatial guidance to young children, scaffolding their instruction depending on the child's age and expertise (e.g., Rogoff, Ellis, & Gardner, 1984; Wertsch, McNamee, McLane, & Budwig, 1980). The amount of spatial talk that a parent uses with his or her child also predicts the amount of spatial talk the child produces and his or her spatial abilities (Pruden, Levine, & Huttenlocher, 2011), thus suggesting that social interactions are an important mechanism through which spatial understanding develops.

Studies also support the culturally situated nature of spatial cognition. The issue of gender differences in spatial ability provides an example of cultural situatedness. Men generally outperform women in spatial tests (Linn & Peterson, 1985; Maccoby & Jacklin, 1974; Voyer, Voyer, & Bryden, 1995). However, this appears to be caused primarily by cultural influences that create a gendered developmental environment where boys are encouraged to engage in spatially involved activities while girls are not. Higher participation in spatial activities not only provides more practice in spatial processes, but may also lead to the development of more effective strategies for spatial tests, which can have notable impacts on performance (e.g., Bethell-Fox & Shepard, 1988; Kail, Carter, & Pellegrino, 1979; Pezaris & Casey, 1991). When men and women are trained to play spatially involved video games (one kind of activity in which boys are culturally encouraged to participate) for several hours, both men and women improve their performance on spatial tests. Notably, women often show greater gains than men, such that the performance gap between genders disappears (e.g., Feng, Spence, & Pratt, 2007; Spence, Yu, Feng, & Marshman, 2009; Subrahmanyam & Greenfield, 1994). Furthermore, there is some evidence that gender differences are declining with time as society reaches higher levels of gender equality and gendered developmental environments become less common (e.g., Linn & Hyde, 1989; Rosenthal & Rubin, 1982; Voyer et al., 1995), although other meta-analyses show that, at least for mental rotation, sex differences have been consistent across time (Masters & Sanders, 1993), even in countries thought to have high gender equality (Nordvik & Amponsah, 1998). Thus, cultural situatedness appears to have strong influences on some aspects of spatial cognition.

Investigations of spatial representations also show cultural differences, further suggesting that the cultural environment in which these representations are learned has a significant effect on their development. For example, Micronesian navigators use complex, mental symbolic representations of their environment that are considerably different from the external symbolic representations used by much of Western civilization (see Hutchins, 1995). Micronesian navigators reported that they think in egocentric relative motion, imagining their ships to be static and considering how external landmarks move relative to them; this allows them to reduce the complexity of their representations. In comparison, Western navigators reported thinking in terms of allocentric absolute motion, accounting for the locations of both their ships and external landmarks in an objective space (Hutchins & Hinton, 1984).

The Vygotskian perspective has added much to our understanding of spatial development, but it also limits itself by focusing primarily on the social and cultural environments in which children interact. By relegating children to a passive learning role, it neglects to consider how children can actively interact with and adapt to the environment around them, changing both their environment and their spatial representations. Furthermore, the Vygotskian account provided relatively little description of the fundamental cognitive processes of spatial reasoning, nor the ways in which, computationally speaking, social and cultural inputs produce spatial abilities.

The Nativist Perspective

A more extreme counter to the Piagetian perspective lies in the nativist perspective on spatial cognition. Whereas Piagetian theory assumes that children can only learn through their sensory experiences, nativists since Immanuel Kant (1894) claim that some spatial knowledge is acquired independent of experience. For example, Kant argued that humans possess an innate ability to organize their sensory experiences of objects and that this organized experience gives rise to the human-made conception of space. Contemporary nativists similarly believe that humans are born with innate spatial knowledge. More specifically, contemporary nativists propose that humans are born with four or five core knowledge systems (Spelke & Kinzler, 2007), two of which are directly involved in spatial cognition: a module for representing objects (limited to representing four objects at once) and a geometric module for representing spatial locations in the environment and their relations through metric properties (e.g., angle and direction).

Many studies support the existence of the innate object representation module. Young infants demonstrate the ability to represent objects, even when they are newborn and have had very little visual experience. For example, Valenza, Leo, Gava, and Simion (2006) found that infants (mean age of 72 hours) who viewed partially occluded objects appeared to perceive and represent the object as one complete object. In addition, some studies show that infants do not develop more advanced cognitive systems for representing objects or entities as they gain more visual experience (e.g., Huntley-Fenner, Carey, & Solimando, 2002; Rosenberg & Carey, 2006), suggesting that spatial cognition systems do not develop with experience as Piagetians and empiricists assumed.

Similar kinds of support have been found for an innate geometric module. The ability to represent geometric information appears despite impoverished prior experiences: children and adults in the Munduruku tribe demonstrate the ability to understand and utilize geometric information from pictures and surface layouts without having any formal education (Dehaene, Izard, Pica, & Spelke, 2006). The dominance of the geometric module has been seen in studies in which children reorient themselves in novel environments by using the geometry of a space, even when nongeometric information is available (e.g., the relative positions of long and short walls in a room; see Hermer & Spelke, 1994, 1996). For example, Hermer and Spelke (1996) showed young children (between 18 and 24 months of age) the location of a hidden object in a room with two short walls and two long walls. The walls were either all white, such that only geometric information about the space was available, or one of the shorter walls was colored blue, such that both geometric and nongeometric information about the space was available. The children were then disoriented and asked to find the hidden object. In both the all-white room and the blue-wall room, children showed evidence of using geometric information, not the color landmark, when reorienting. Furthermore, children cannot reorient themselves or locate objects by using the geometry of object arrays (e.g., when objects were visually indistinguishable, but their arrangement formed a distinctive shape; Gouteaux & Spelke, 2001; Lourenco, Huttenlocher, & Vasilyeva, 2005). This suggests that children's initial spatial understanding is limited to environment geometries and cannot transfer to object geometries, as predicted by a geometric environmental module. Even adults tend to rely primarily on a space's geometry when they are disoriented and under verbal or spatial interference (Hermer-Vazquez, Spelke, & Katsnelson, 1999).

However, many of the patterns found in reorientation studies could be explained by a number of models (see Cheng & Newcombe, 2005, for a review), not just a model in which reorientation involves only geometric information and in which featural information is separate and does not contribute to reorientation. For example, the patterns could also be explained by a reorientation system in which geometric and featural information are separate but both influence reorientation, such that geometric information codes the metric properties of space, and featural information is "glued on" to refine the spatial representation (Cheng, 1986). Alternatively, patterns could be explained by a system in which geometric and featural information is integrated, such that initial input may be modular, but these modular inputs are eventually integrated into a central system that accounts for input characteristics and the individual's learning history (Newcombe, 2002). Computational evidence applied to rodent data also suggests that simpler models that use visual features for reorientation may be able to explain reorientation better than the existence of a geometric module (Sheynikhovich, Chavarriaga, Strösslin, Arleo, & Gerstner, 2009).

The nativist perspective also runs into several limitations. Because it focuses on innate knowledge systems, it necessarily puts environmental input and later development at a secondary level. Some nativists have argued that the maturation of specific brain regions can explain any changes that are not explained by an innate system (Diamond, 1991). However, this claim is computationally implausible because learning effects in spatial ability have often been found and therefore must be co-present with developmental change. For example, Connell and Stevens (2002) developed an automated tutor that trained learners' visual-spatial skills by choosing training tasks based on the individual users' competence, aiming to situate learning at each learners' developmental level. In a 10-week study, students of 7 to 11 years of age who used the tutor showed significant improvements on challenging visual-spatial tasks, and performance on the tutor was significantly correlated with performance on visual-spatial tasks after training (D. A. Stevens et al., 2003). Therefore, it appears that learners at the same starting maturational level can improve their spatial abilities at different rates depending on environmental input (in this case, the tutor intervention), which is likely to be associated with differential developmental changes. Furthermore, the nativist claim ignores much research that shows that the environment has significant influences on neurological development (see Stiles, 2011, for a review); for example, monocular deprivation can prevent the primary visual cortex from organizing into its regular ocular dominance columns, showing that changes in environmental input can alter brain connectivity. Thus, the nativist perspective cannot fully explain the mechanisms through which new spatial knowledge develops.

The Neoconstructivist Perspective

The neoconstructivist perspective was developed to address the shortcomings of Piagetian, Vygotskian, and nativist claims and resulted in a framework that is more computationally plausible. Neoconstructivism claims that the mind is biologically prepared to interact with a predictable environment, and it is through these interactions that spatial cognition develops. The perspective was formed primarily from Piaget's original constructivist theories of development, similarly claiming that knowledge is built from interactions with the physical environment. However, unlike Piaget and drawing some influence from nativism, neoconstructivist theories argue that we do not start as a blank slate and are instead equipped with some innate preparedness for learning spatial cognition.

Many studies have found results that conflict with nativist claims and support neoconstructivist theories. In the case of object recognition, studies show that infants develop spatial principles (including cohesion and continuity, which are included in the nativist object recognition module) during their first few months of life through visual-manual exploration (e.g., Needham, 2009; Soska, Adolph, & Johnson, 2010). Infants may also use or weigh spatial principles differently depending on their age, the problem situation (Keen, 2003), and their prior experiences and interactions with the world (Wilcox & Woods, 2009). For example, Woods and Wilcox (2006) found that infants do not utilize color differences to individuate objects, even though infants are able to perceive these color differences. They suggest that this is because infants know, through prior experiences, that color is not a constant feature of objects but can change depending on the context. To test this claim, Wilcox and Woods (2009) manipulated infants' prior experiences with color such that the color of an object predicted the function that an object could complete (e.g., a green can could only be used to hammer pegs, while a red can could only be used to pour salt), thus making color a constant and relevant feature with which to differentiate objects. The manipulation heightened infants' sensitivity to color features during a later test event.

These conclusions fit with a computational model explored by Munakata and colleagues (Munakata, McClelland, Johnson, & Siegler, 1997), which tested whether object representations are graded and develop with experience. Their connectionist model simulated behavior in an object permanence task, in which infants must represent occluded objects and respond to them perceptually (by looking) or manually (by reaching). The model consisted of a single representational system that learned to represent occluded objects through repeated exposure to objects being occluded and then reappearing. This representational system was connected to two output systems (one of which represented perceptual responses, while the other represented manual responses). To stay consistent with experimental observations of infants' looking and reaching behaviors, the manual response system was set to begin learning only after the perceptual response system had partially learned about occluded objects and only learned at a tenth of the rate of the perceptual response system. Munakata and colleagues' model of adaptive processing was able to closely simulate actual infant behavior, showing that infants' spatial development can be accurately produced under a cognitive system that gradually develops spatial representations through visual and manual experience. However, other competing connectionist models also fit infants' behaviors while using different assumptions. For example, Mareschal and colleagues' model (Mareschal, Plunkett, & Harris, 1999) assumed that occluded objects require a stronger, more consolidated representation of the object and that manual responses require greater representational coordination than do perceptual responses; this model was still able to develop object recognition. Thus, it is possible that the spatial representations that form through experience are not graded but must instead be more consolidated from the start and that the precise interaction between visual and manual experiences may need to be revised.

Evidence has also been found against the nativist geometric module. Learmonth, Newcombe, and Huttenlocher (2001) found that young children can use both geometric and nongeometric information when they are reorienting themselves. In their study, children used nongeometric landmarks (i.e., objects situated in the environment; in this case a bookcase and a door) in a room to reorient themselves, so long as the landmark objects were permanently located. The geometric module does not explain the use of such nongeometric behavior, suggesting either that the module does not exist or that more innate modules for environments must exist that involve nongeometric spatial information. The geometric module also cannot explain significant changes over time that are found in other types of human navigation. For example, infants initially code locations using sensorimotor coding and then shift over time to nonegocentric coding (e.g., cue learning and place learning). Specifically, when infants were trained to turn their heads toward stimuli in one direction and were then moved to the opposite side of the room, 6-month-olds and 11-month-olds relied on sensorimotor coding (i.e., they continued to turn their head in the same direction, not toward the stimuli), whereas 16-month-olds used dead reckoning (i.e., they turned to the opposite direction, taking their movement to the other side of the room into account). When a landmark was present in the room that could be used for cue learning, some 11-month-olds stopped relying on sensorimotor learning (Acredolo, 1978). Nine-month-olds also showed a reliance on sensorimotor learning during search tasks even when cues were available to use, and they only began to develop cue learning at the end of their first year (Bremner & Bryant, 1977). Thus, spatial systems for navigation show significant improvements with age, which cannot be explained by the nativist approach.

It is possible that infants have the capability to use all types of spatial systems at a very young age similar to nativists' claims, rather than developing these capabilities later on, but they still need to learn which coding system to use when these information sources disagree (Newcombe & Huttenlocher, 2003). In several studies, infants as young as 6 months of age do not consistently rely on sensorimotor coding when cues are especially salient, implying that infants have the ability to use both sensorimotor and cue learning at an early age but have not learned which to choose when they conflict (Acredolo & Evans, 1980; Baillargeon, 1986). Studies also suggest that infants as young as 5 or 6 months are capable of dead reckoning so long as the movement involved is something they normally perform at that age, such as turning from side to side or rolling (Kellman, Gleitman, & Spelke, 1987; Landau & Spelke, 1988). As for more complex dead reckoning, Bullens and colleagues (Bullens, Iglöi, Berthoz, Postma, & Rondi-Reig, 2010) found that 5-, 7-, and 10-year olds were all capable of successfully using dead reckoning, although only 7- and 10-year olds used it spontaneously. Although this alternative fits with nativist claims, the core knowledge systems would still need to be revised to cover these other types of navigation systems. Furthermore, learning to use one coding system over another appears driven by motorical (e.g., Acredolo, 1978; Bai & Bertenthal, 1992) and visual (e.g., Bertenthal, Campos, & Barrett, 1984) experience as infants learn the types of information (and the types of coding needed to acquire that information) that are most useful in different situations. Thus, the nativist approach still cannot fully explain the relation between visual and manual experience and spatial development.

There are still some issues with the neoconstructivist approach because much variation within neoconstructivist theories has yet to be resolved. One question is how strongly spatial development is domain-general or whether it is primarily domain-specific. A second question asks whether spatial development is primarily driven through implicit learning about spatial properties, which is then followed by more explicit spatial knowledge or vice versa. More research is needed to delineate whether the nativist or neoconstructivist approach better explains empirical data on spatial development and to help answer the questions that still divide theories within the neoconstructivist approach.

Future Directions

The central questions in this chapter have yet to be fully answered. Although many theories have been posed, more converging evidence from behavioral, neuroscience, and computational studies can further clarify these theories. The practical applications of spatial cognition have also continued to be a notable topic in the spatial cognition literature.

As discussed at the beginning of this chapter, many studies suggest that spatial ability is related to performance in other important basic skills (e.g., math and science) and specific disciplines, but other studies have found considerably weaker associations. One issue may be the many different components of spatial cognition. Certain components may be more important for performance in specific fields, meaning that each separable component would need to be tested. There is also some debate on whether the current measures used are accurately measuring specific components, and a number of studies have focused on creating and validating new spatial measures to provide greater reliability.

There has also been an initiative to investigate whether spatial ability can be improved through training and consequently improve ability in other fields. Many successful interventions have been found, including video game training (e.g., Feng et al., 2007) and the use of two- and three-dimensional representations in physics classes (McAuliffe, 2003); more research can be done to find more successful interventions and to uncover the cognitive mechanisms that underlie training improvements.

Finally, as technology advances and more spatial tools become available for everyday use (e.g., smartphones, GPS, augmented reality tools), it would be interesting to see how these external aids can be used to improve spatial ability and potentially other skills, and whether any improvements are only available when the tool is in use or whether changes are more permanent. With a combination of basic and applied research on spatial cognition, we can develop a complete picture of how spatial cognition plays into our everyday lives.

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