Advanced Review

Development of spatial cognition

Marina Vasilyeva[1,*] and Stella F. Lourenco[2]

Spatial cognition plays an essential role in everyday functioning and provides a foundation for successful performance in scientific and technological fields. Reasoning about space involves processing information about distance, angles, and direction. Starting from infancy, children display sensitivity to these spatial properties, although their initial skills are quite limited. Subsequent development during early childhood and through the elementary school years involves gradual improvement in the use of individual frames of reference (i.e., *egocentric* and *allocentric*), as well as in the ability to flexibly combine different types of spatial information. Similarly, there is a relatively long progression from the starting points, when infants and young children display sensitivity to distance and form simple spatial categories, to more mature spatial competence when older children and adults integrate distance and categorical information hierarchically. Such developments are associated with both the maturation of specific brain regions and accumulating experience, including interactions with the physical world and the acquisition of cultural tools. In particular, the mastery of symbolic spatial representations, such as maps and models, significantly augments basic spatial capabilities. While growing evidence implicates both biological and experiential factors in the development of spatial cognition, a deeper understanding of the mechanisms that underlie the developmental process requires further investigation of how such factors interact to produce organisms that function competently in their environments.

How to cite this article:
WIREs Cogn Sci 2012, 3:349–362. doi: 10.1002/wcs.1171

INTRODUCTION

The development of spatial cognition is a one of the most subtle, yet critical, aspects of intellectual growth. Although early spatial skills may not receive as much recognition from caregivers as children's accomplishments in language acquisition or counting, these skills provide an essential foundation for everyday functioning. A variety of basic tasks, such as locating objects and even simple locomotion, involve processing information about space. Developments taking place during childhood provide a basis for solving more complex spatial problems embedded in daily activities of adults, for example, finding a route through a neighborhood or assembling furniture. The diversity of tasks that involve thinking about space makes it difficult to provide a concise definition of this cognitive domain. Nevertheless, we would suggest that a key aspect—the representation of location—unites much of spatial cognition. To remember or reason about location, one must process information about distance (or length), angle, and direction (or sense: left vs right). Because such cues are specified in relation to a particular point of origin or a chosen frame of reference, spatial cognition is relational in nature. For example, determining the shape of an object involves reasoning about angles and relative side lengths; locating objects within a large-scale environment involves reasoning about distances and directions, which can be determined either relative to a stable reference point or relative to an individual moving through that environment.

In addition to everyday functioning, spatial cognition is critical for success in science and technology.[1] Reasoning about space is at the core of professional fields of geography, astronomy, geology,

*Correspondence to: vasilyev@bc.edu

[1]Lynch School of Education, Boston College, Chestnut Hill, MA, USA

[2]Department of Psychology, Emory University, Atlanta, GA, USA

architecture, and engineering. The involvement of spatial thinking in some other domains, such as biology or chemistry, may be less obvious, yet breakthroughs in these domains have often depended on the understanding of configurational information (e.g., the relative positions of atoms).[2] A striking illustration of the power of spatial thinking is the discovery of DNA structure, whereby accurate visualization of DNA enabled researchers to explain the properties underlying reproduction of genetic material. Historic accounts of scientific discoveries are supplemented by contemporary findings that highlight the association between spatial skills and academic accomplishments in math and science.[3]

Recognizing the significance of spatial cognition, this paper focuses on issues related to its origins and development. Research on spatial development seeks to identify starting points and to characterize subsequent changes and continuity in reasoning about space, as well as to understand the mechanisms underlying development. This line of research began with the work of Jean Piaget.[4] Although many of his claims have been challenged,[5] his theoretical framework and empirical approach have had a profound impact on subsequent research. One of his major contributions was to outline a set of critical themes in the development of spatial cognition. These themes concern the frames of reference (allocentric and egocentric) and types of information (e.g., metric and categorical cues) used to identify and locate objects. Another important theme concerns the acquisition of symbolic spatial tools and their role in children's reasoning about space. Throughout the paper, we trace major themes in the study of spatial development as they unfold across different age groups.

FRAMES OF REFERENCE: EGOCENTRIC AND ALLOCENTRIC CODING

Researchers distinguish two fundamental ways in which location can be represented: *egocentric (or viewer-dependent) coding*—that is, coding relative to oneself, and *allocentric (or viewer-independent) coding*—that is, coding relative to external features of the environment. Because the egocentric strategy is tied to the observer, it can be used either when the observer remains stationary or when he/she moves and is able to keep track of the movement, a process known as *dead reckoning* (or *path integration*). Allocentric coding provides a more flexible basis for solving spatial tasks, as it does not depend on the viewer's current position or the ability to update one's changing relation to the target location while moving. Two major types of allocentric coding are known as *cue learning* and *place learning*. When representing the location of an object, the former involves the use of adjacent landmarks as direct cues to the object's location, whereas the latter involves the relation between the object and distal landmarks in the environment.

Emergence of Allocentric Coding in Infancy

Although early spatial representations were originally described as purely egocentric,[4] later research provided evidence that infants can use external features of the environment to locate objects.[6–9] This evidence was obtained using a paradigm in which children, after being repeatedly exposed to an engaging stimulus presented in the same location, were moved to a novel position; their direction of looking indicated where they expected the stimulus to appear. Investigators found that when the stimulus was adjacent to a salient landmark, 8.5 month olds used the landmark as a cue to object location, whereas younger infants did not. When there were no adjacent landmarks, but the stimulus could be coded in relation to distal landmarks, 8.5 month olds showed mixed performance. Only at 12 months did the majority of infants consistently use relational landmark information.[8] It has been suggested that the onset of crawling around 8–9 months may play a role in the emergence of allocentric coding in the form of cue learning. Further experience with independent locomotion may facilitate place learning by providing children with opportunities to observe and approach object arrays from different directions.[8]

Early Development of Dead Reckoning

Around the time when children begin to use allocentric cues, they start employing another strategy that allows them to locate objects from novel positions—dead reckoning. Evidence suggests that a basic capacity to update egocentric representations by keeping track of one's movement emerges within the first year of life.[10] By 9 months, infants can compensate for simple changes in their position, such as translation along a straight line[11] or rotational movements.[12] However, as the complexity of displacement increases, children have more difficulty in keeping track of their changing relation to target locations. Only at 12 months do children begin solving problems involving both translation and rotation, and even then their performance on tasks that require dead reckoning is not as strong as on those that can be solved using adjacent landmarks.[8]

FIGURE 1 | Photograph of the experimental set up used in the studies of Huttenlocher, Newcombe, and colleagues.[13–15] This photograph shows a child searching in the sandbox for the hidden object.

To examine further development of dead reckoning, Newcombe and colleagues[13] presented 16–36 month olds with a search task: children had to find a toy hidden in a rectangular box after being turned around and moved to the opposite side of the box (Figure 1). In the absence of landmarks, locating the object required updating both lateral and rotational components of this movement. Although children performed at above-chance levels, they were significantly less accurate than when they broke gaze with the target location but remained stationary. Interestingly, performance following movement was comparable across the age range tested. Thus, the capacity to keep track of complex movements appears to show little improvement between 16 and 36 months of age, perhaps reflecting relative stability in motor development during the toddler years.[5]

Spatial Reorientation in Toddlers

In many real-life situations it is difficult, or even impossible, to continuously update one's relation to a target location while moving. In this case, individuals must rely on features of the environment to reorient themselves. In the last decade, there has been a proliferation of studies examining the emergence of this ability, beginning with the work of Hermer and Spelke[16,17] who adapted a disorientation task originally used with animals[18] to investigate spatial reorientation in 18–24 month olds. Toddlers were tested in a small rectangular room: after observing a toy being hidden in one of the corners, they were picked up and spun around with their eyes covered. Following disorientation, children were encouraged to find the toy. They searched either in the correct corner or the corner with identical geometric properties (e.g., from the child's perspective, the corner was viewed as having the long wall to the left of the short wall; Figure 2). This search pattern showed that toddlers were capable of relying on geometric shape of the environment to reorient themselves—they combined spatial features of the room (relative side lengths) with the sense of direction relative to self (left vs right) to represent the target corner. Subsequent research has extended this finding to spaces of different shapes (i.e., isosceles triangle[19]; rhombus[20]; and octagon[21]) and sizes (i.e., larger rooms[20,22]; smaller rooms[23]; and models[19]).

Although toddlers' ability for spatial reorientation is well established and widely recognized, there is considerable debate concerning the mechanisms underlying this phenomenon. Hermer and Spelke[16] suggested that the process of reorientation is modular—based solely on the geometry of the surrounding space, to the exclusion of other types of environmental cues. This claim was based on the errors committed by toddlers when nongeometric information was available. In one version of the disorientation task, a blue wall could be used to differentiate the correct corner from its geometric equivalent in a rectangular room. Despite having noticed the different-colored wall, toddlers did not use it when searching for the hidden object, indicating that they failed to combine geometric and nongeometric information.

However, later work revealed the use of nongeometric features by toddlers in disorientation tasks conducted in large spaces.[22] To account for these findings, more recent perspectives have addressed how young children combine geometry and landmarks in the process of reorientation under different conditions. Lee, Spelke, and colleagues[24,25] proposed a two-stage model in which organisms first reorient by reference to a three-dimensional (3D) environment (e.g., surrounding enclosed space) and later use associative processes to link two-dimensional (2D) features (e.g., blue wall) to the target location. Lee et al.[25] found that children tested in a circular room with three containers positioned at the vertices of an equilateral triangle only searched at the correct location when the object was hidden in a featurally distinctive container (Figure 3). They failed to choose between two identical containers, suggesting that when geometry must be inferred, rather than available as a 3D enclosure, visual cues are used only associatively as direct indicators of the hidden object's location, rather than as a guide to reorientation.

In contrast, Newcombe and colleagues[26,27] proposed an adaptive combination model, which

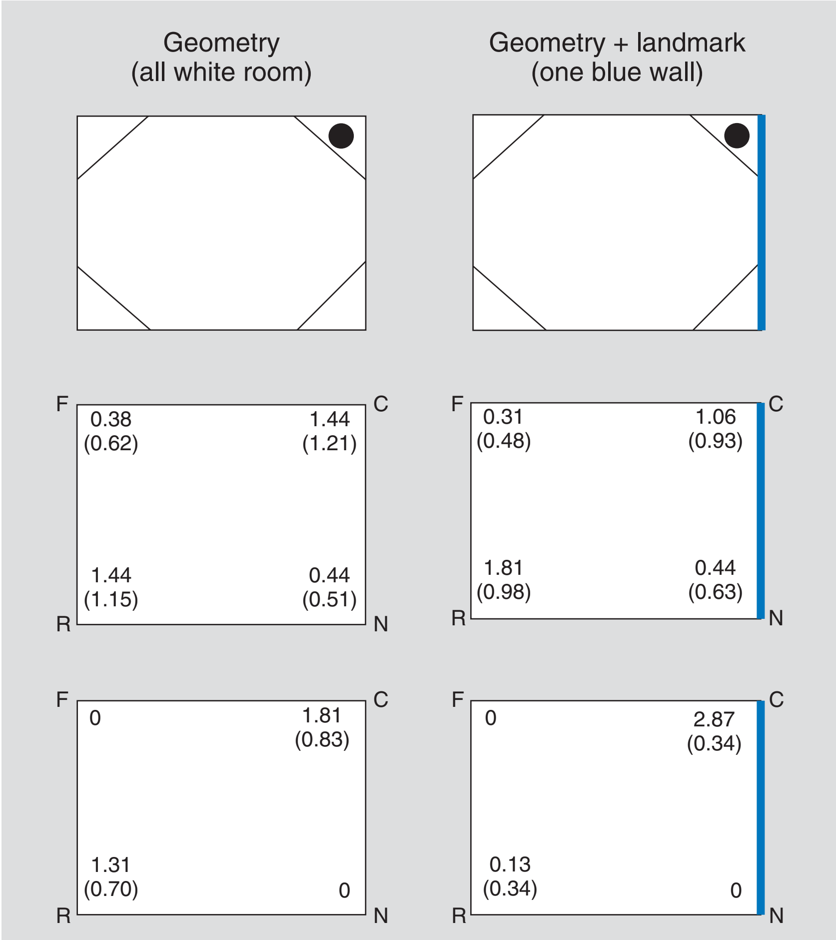

FIGURE 2 | An illustration of the conditions and results in the Hermer and Spelke study.[16,17] *Top row*: Two experimental conditions—Geometry condition, where the target location can be coded as being in the corner with the long wall to the left of the short wall; and Geometry + Landmark condition, where the target location can also be coded as being adjacent to the blue wall. *Middle row*: Toddlers' mean number of search responses (standard deviation in parentheses) at each of the corners. *Bottom row*: Adults' mean number of search responses (and standard deviations). 'C' and 'R' correspond to the correct corner and the rotationally equivalent corner, respectively. 'N' and 'F' correspond to the corners nearest and farthest from the correct corner, respectively. (Reprinted with permission from Ref 16. Copyright 1994 Nature Publishing Group)

holds that the use of geometry and nongeometric information depends on relative weights associated with available cues. These weights are determined by factors such as cues' salience and perceived reliability, the latter depending largely on prior experience and learning history. For example, more distal landmarks are likely to be assigned greater weights during navigation because objects that are visible from farther away tend to be large and immovable, which increases their salience and reliability as a spatial cue. According to the adaptive combination model, a weight is initially established for each type of cue (i.e., geometric vs nongeometric) during encoding, and these weights are then combined following Bayesian rules, whereby greater reliability is associated with less variance and thus given greater weight.[27]

Despite disagreements concerning modularity, there is reason to believe that geometric information is highly salient and may be especially prepotent to young children. What might account for this prepotency, especially under conditions of disorientation? Recent work points to the more general property of scalar dimensions, which involve inherently ordered stimulus values. Lourenco, Huttenlocher, and colleagues[28,29] examined reorientation in a square space. The task was similar to that used by Hermer and Spelke,[17] except that the shape of the surrounding space could not be used to distinguish the corners. What could be used, however, were the cues on the walls. In some conditions, the cues were scalar, that is, ordered along a continuous dimension such as relative size (i.e., smaller vs larger dots) or relative luminance (i.e., light vs darker gray); see Figure 4. In other conditions, the cues were non-scalar (i.e., arbitrary exemplars from a specific category: blue vs red, pattern vs no pattern). In the scalar conditions, children searched at the appropriate corners (e.g., the corners with the smaller dots to the left of the larger dots), whereas in the other conditions, they searched randomly. The authors suggested that the mapping of scalar information onto directions in space may be facilitated by the inherent directionality (order) along the scale. It is this directional analogy, absent in categorical conditions, which may support the left/right

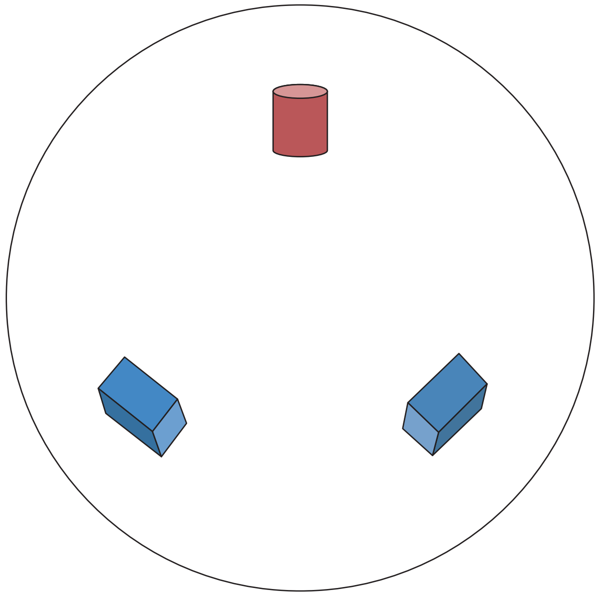

FIGURE 3 | The spatial layout used by Lee and colleagues.[25] Objects were placed at the vertices of an equilateral triangle in a circular space. There was one unique object (red cylinder) and two identical objects (blue boxes). (Reprinted with permission from Ref 25. Copyright 2006 Sage Publications)

mapping needed to locate a hidden object following disorientation.[29] Note that this rationale similarly applies to relative side length in spaces such as rectangular rooms.

Spatial Frames of Reference in Older Children

Although infants and toddlers are capable of using egocentric and allocentric representations, this early ability is quite limited. For example, infants' reliance on environmental landmarks is contingent upon their salience and proximity[6]; toddlers' use of geometric cues for reorientation in small spaces is not integrated with landmark cues.[16] Subsequent growth of spatial cognition involves both the improvement in the use of individual spatial representational systems (allocentric and egocentric), and in the ability to integrate them.

Nardini and colleagues[30] investigated the development of allocentric spatial representations between 4 and 8 years of age. To examine children's ability to code spatial relations in a viewer-independent manner, investigators created a search task that precluded solutions on the basis of updating one's position during movement (dead reckoning) or matching the current view with the previously stored one (view matching). Starting at age 6, children were able to use the external structure of the environment to infer the target location from a novel position, whereas younger children failed the task. Prior findings suggesting that toddlers and even infants can locate objects after moving to new positions might be due to utilizing tasks that allowed for dead reckoning[6] or view matching,[16] neither of which represents a purely viewer-independent process. The findings of Nardini et al.[30] indicate that true independence from one's own viewpoint is a gradually developing aspect of spatial cognition.

Another important development that occurs around 6 years concerns the ability to combine different types of cues in spatial reorientation. While toddlers often ignore nongeometric information on disorientation tasks, older children combine geometry with nongeometric features (e.g., color) under the same conditions.[16] Spelke and colleagues[31] have proposed that the development of spatial language plays a key role in this combination process. Alternatively, the adaptive combination model described above[27] suggests that developmental changes in the use of geometric and nongeometric properties may be related to learning which environmental cues are relevant and reliable for particular spatial tasks and how different cues should be weighted to optimize performance.

While the ability to integrate geometric and nongeometric properties of the environment becomes robust around the age of 6, the ability to integrate environmental features with egocentric representations develops later. Nardini et al.[32] examined this ability in children (4–8 year olds) and adults who were asked to reproduce object location under several experimental conditions: participants could rely on external landmarks (viewer-independent cues) or self-motion (viewer-dependent cues), or both. When both strategies were possible, adults integrated them in a weighted average, whereas children alternated between using allocentric and egocentric cues without combining them. Thus, the ability to integrate different reference frames within a common system of spatial representation follows an extended course of development. Once achieved, this ability provides an advantage by reducing response variance and thus improving overall accuracy.

METRIC AND CATEGORICAL REPRESENTATIONS OF SPACE

Advanced forms of both allocentric and egocentric coding involve information about distance and direction. In particular, this information is required to encode object location relative to distal landmarks or to keep track of changes in one's own position during movement. Spatial representations that specify distance and direction from a point of reference are

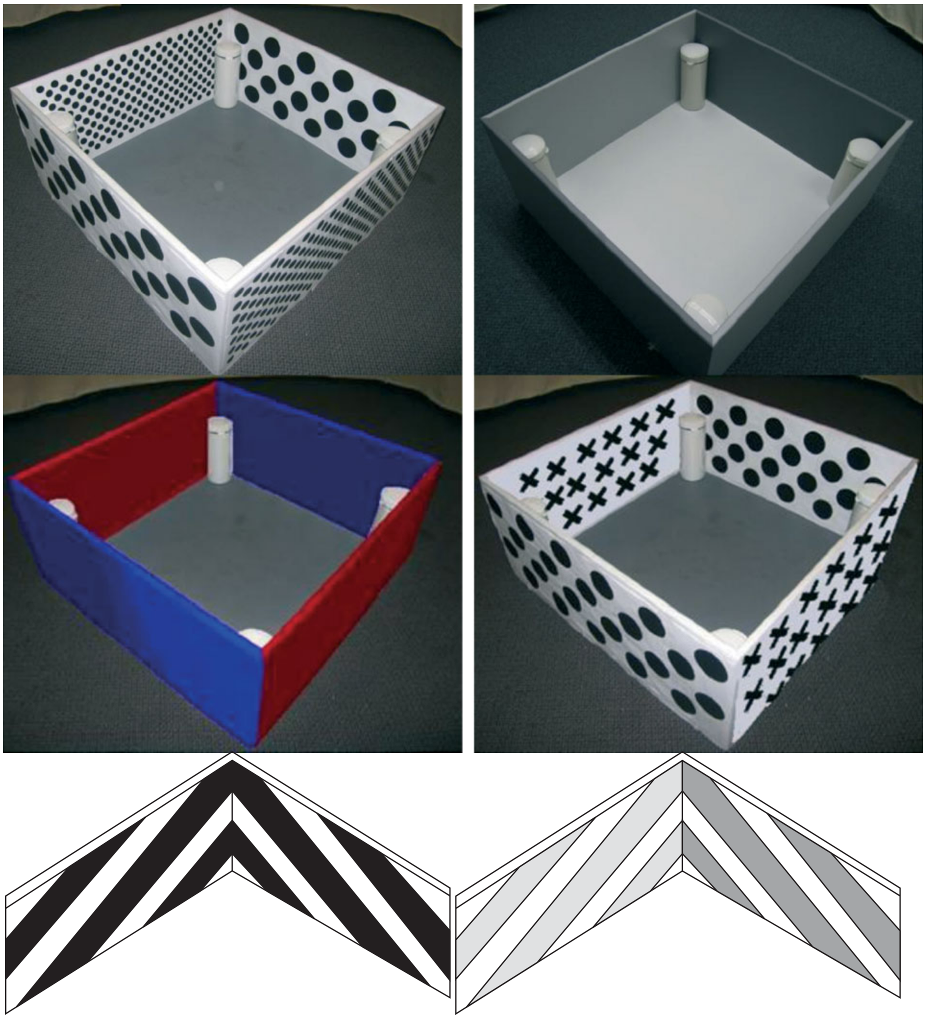

FIGURE 4 | Stimuli used in the studies of Huttenlocher, Lourenco, and colleagues.[28,29] Top row: Square space with scalar dimensions on the walls. The left picture shows the relative size condition[28] (Reprinted with permission from Ref 28. Copyright 2007 Wiley-Blackwell) and the right picture shows the luminance condition (Reprinted with permission from Ref 29. Copyright 2009 Elsevier). Middle row: Square space with non-scalar dimensions. The left picture shows the color condition (red vs blue) and the right picture shows the pattern condition (Xs vs Os).[28] Bottom row: An illustration of the cues used by Lourenco et al.[29] The left illustration is an example of one of the corners in the non-scalar (oblique lines) condition. The right illustration represents a composite of scalar (luminance) and non-scalar (oblique lines) information.

referred to as *metric* or *fine-grained representations* (e.g., the museum is 100 m south of the theater). Alternatively, spatial properties of objects and environments can be represented at a coarser level using category information. In these *categorical representations*, object locations are coded with respect to a larger spatial region, without specifying exact coordinates within that region (e.g., the museum is in the center of the city). Traditionally, it was assumed that children first rely on categorical coding and later start using metric cues, such as distance or length.[4] More recent work, reviewed below, reveals much earlier sensitivity to metric information. Furthermore, in the course of development, children begin combining metric and categorical cues when coding object size and location.

Categorical and Metric Coding in Infancy

Considerable advances in our knowledge of infants' ability to use spatial information have been made possible through the use of looking-time paradigms, such as habituation/dishabituation and violation of expectation.[33,34] Using this methodology, researchers have found that infants distinguish spatial categories, such as above versus below and left versus right.[34,35] Categorical spatial representations undergo changes during infancy. Younger infants (3–4 months) form categories that are tied to the objects used during learning, whereas older infants (6–7 months) form more abstract spatial categories that extend beyond these objects.[36]

In addition to their ability to represent categorical information, infants show sensitivity to metric cues. Baillargeon[37] has shown that infants represent *spatial extent* (e.g., object height). Similar to categorical coding, the ability to represent metric properties emerges early in development (4.5 months) but undergoes developmental change, as representations become more precise in older infants (6.5 months). Whereas height captures the linear extent of an object, other metric cues, such as angular size, are also important for identifying objects and specifying locations, and there is evidence that infants are sensitive to such information, distinguishing, for example, between acute and obtuse angles.[38–40] Early sensitivity to metric cues manifests itself not only in infants' ability to code spatial dimensions of an object, but also in their ability to code *distance* between objects. For example, 5 month olds who watched a toy being repeatedly hidden and retrieved at a particular location, looked longer when the toy emerged some distance away.[41]

This growing body of work demonstrates that infants are sensitive to metric information, including length, angle, and distance, which enables them to identify object size, shape, and location. However, the nature of infants' spatial representations is not fully understood. Most of the information concerning this developmental period comes from studies utilizing looking-time paradigms and questions have been raised regarding the use of these techniques.[42] In particular, differences in looking times (the main outcome variable in infant studies) may not reveal conceptual representations in infants as much as they reveal lower-level perceptual discrimination.[43] Research on older children has the potential to shed light on phenomena observed earlier in development by providing more direct assessments of spatial cognition and its limitations.

Coding Metric Information by Toddlers

Toddlers' ability to code metric information has typically been tested with search tasks, where they have to locate an object hidden in a small-scale space.[44,14] Their performance in such tasks indicates considerable accuracy in the use of distance cues. A closer look at the studies demonstrating the early distance coding reveals a common feature that could be critical to successful performance. Namely, these studies typically involve an object presented within a salient frame of reference, such as a sandbox. The frame may provide a perceptually available standard, allowing children to code distance or length in relation to that standard.

The hypothesis that young children may rely on relative cues in coding spatial extent received support from a study by Huttenlocher, Duffy, and Levine.[45] In this study, 2 year olds were able to match objects by height when these objects were presented in containers of a fixed height, but not when they were presented without containers (Figure 5). Children's success appeared to depend on whether the object size could be coded relative to another object (e.g., container). Note, though, that the use of relational information in children of this age is not likely based on a computation of ratios for lengths or distances. It is more likely that early metric coding involves a form of perceptually based judgment, which automatically registers the relation between the object and its surroundings.[46,47]

Another remarkable feature of toddler's spatial cognition is their ability to integrate categorical and metric cues. The use of categorical information is generally helpful in reconstructing locations since metric representations are imprecise and relatively short-lived. Evidence of combining metric and categorical cues comes from search tasks: when looking for an object hidden in a rectangular box, 1- and 2 year olds produce responses that are slightly biased toward the box's center.[14] This bias has been interpreted as evidence that children treat the rectangular frame of the box as a single spatial category with a prototypical location at its center. Their estimates are thus adjusted toward the category's prototype.

Further Development of Spatial Coding

Between the ages of 4 and 12, the accuracy of performance on tasks that require coding object size and location improves substantially.[48–51] One reason for this improvement is the increased memory for fine-grained (metric) information.[51] In addition, Newcombe and Huttenlocher[26] proposed that age-related improvements are due, in part, to the development of a hierarchical coding system, which integrates metric and categorical information. Although the ability to combine metric and categorical cues has been reported in toddlers, their use of this process is limited. They rely on categories formed by perceptually available boundaries and adjust metric estimates along a single dimension. Starting at age 6, children impose mental subdivisions on spatial layouts, thus forming categories for which there are no physically defined boundaries.[14] Around the age of 7, children start integrating information about spatial categories that

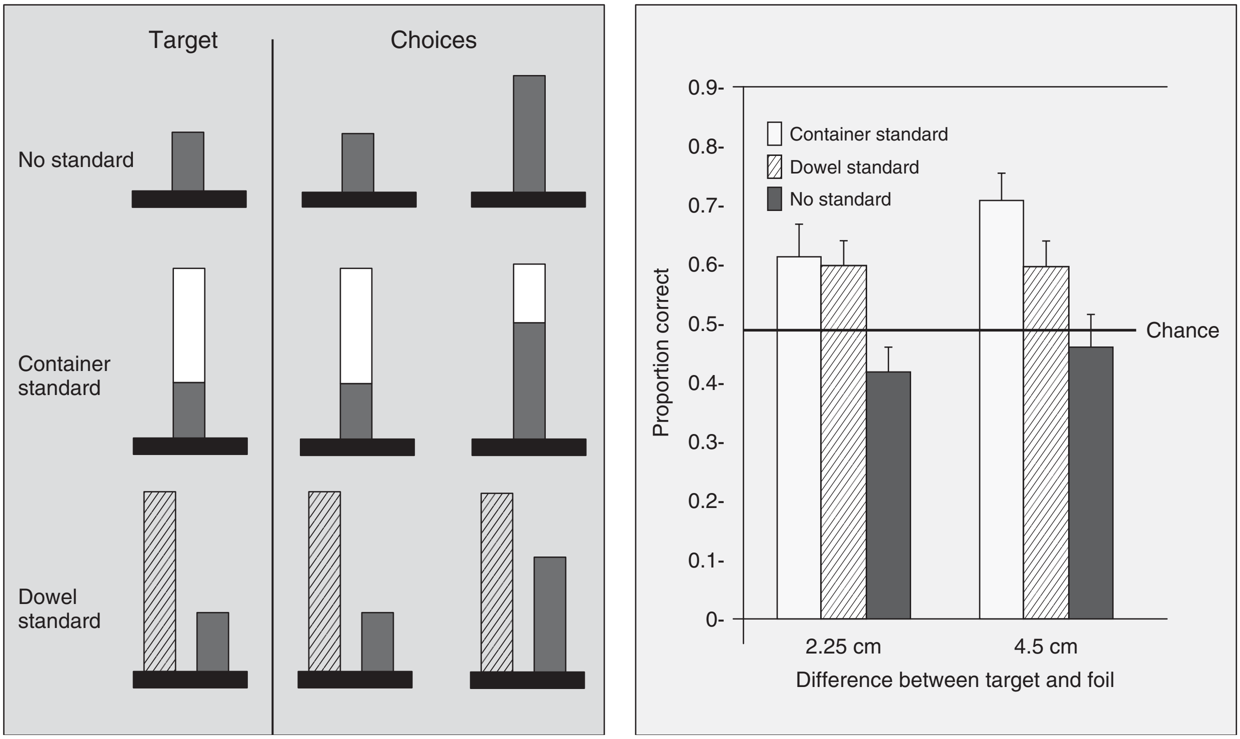

FIGURE 5 | Stimuli (left panel) and results (right panel) for each of the conditions in Huttenlocher, Duffy, and Levine.[45] Left: In all conditions, children were first presented with the target dowel, which either appeared without a standard (top) or with one of two types of standards (middle and bottom). They were then presented with two objects (target and foil), and asked to select the target. Right: Mean accuracy (and standard error) as a function of condition. (Reprinted with permission from Ref 45 Copyright 2002 Sage Publications)

are formed along two dimensions.[48] Further developments of categorical reasoning occur in late childhood (12–16 years) when children increase the use of spatial clustering (i.e., grouping objects based on proximity or membership in a spatial region) on tasks that require remembering multiple locations.[49,51]

Plumert and colleagues have pointed out that some tasks reveal a U-shaped developmental pattern in categorical bias, with 11 year olds showing less bias than 7–9 year olds or adults.[51] They explain this developmental pattern by proposing that reliance on categorical coding continues to increase until adulthood, whereas memory for fine-grained distance information appears to reach a plateau around 11 years. As a result, 7–9 year olds, whose fine-grained memory of location is very imprecise, rely on categorical information more than 11 year olds; adults rely more on categorical information because their categorical coding is much stronger than that of 11 year olds. It should be noted that the extent of reliance on categorical information is not solely a function of age; it also varies depending on task structure and perceptual salience of categorical cues, such as boundaries between spatial regions. Yet, the general age-related tendency is for older children to form more differentiated categories. The advantage of the coding system that involves more differentiated divisions of space is that using such divisions to adjust metric estimates significantly constrains the variability of responses, leading on average to higher accuracy.[51,52]

Another significant development taking place in school-aged children concerns the ability to code location in relation to multiple distal landmarks.[53–55] Overman and colleagues[54] showed significant improvements in accuracy around 7 years of age on tasks that require using distal landmarks in a large-scale space. This line of development continues between ages 7 and 12 through further advances in the ability to use a configuration of distal landmarks to infer object location.[53] Thus, there appears to be a significant window of time between the emergence of distance coding within a small enclosed space along a single dimension[56] and mastering the ability to integrate distance from multiple landmarks to code location in a large space.[53,54] This time lag may be linked to functional maturation of the hippocampus,[57] as well as experience with navigation and use of landmarks.[5] Furthermore, learning to use symbolic depictions of space, such as maps and models, where multiple distal landmarks can be seen simultaneously, may direct children's attention to the relations among landmarks when reasoning about locations.

USE OF SYMBOLIC TOOLS IN SPATIAL REASONING

The uniquely human ability to use symbolic representations augments basic spatial capabilities by allowing us to acquire and communicate information about space beyond that available from direct experience. Symbolic spatial representations come in a variety of forms—from 2D 'you are here' maps to 3D models and interactive media, such as a GPS. As with any symbolic system, there are elements of maps and models that are arbitrary. For example, a location of a village on a map may be marked with a red star or a black dot. However, unlike words whose linguistic form is completely unrelated to the concepts they represent, maps/models typically preserve characteristics of the spaces they represent. Because the properties of symbolic spatial representations are systematically linked to the properties of the referent spaces, some researchers call maps and models 'motivated symbols'.[58] Learning how to use these symbols is a gradual process that depends on the level of cognitive development in general and spatial reasoning in particular. To be able to use a map, one has to establish the correspondence between individual symbols on the map and objects in the real world (*object correspondence*) and also between the spatial relations on the map and those in the real world (*relational correspondence*).

The emergence of the ability to use simple representations of space was explored in a series of studies by DeLoache.[59,60] In these studies, children had to determine an object's location in a spatial layout (e.g., a room) based on information obtained from another layout (e.g., a model of that room). Starting at the age of 2.5–3 years, children performed successfully on this task. Successful performance, however, did not require establishing the correspondence of spatial relations between layouts. Because target objects always had unique non-spatial features (color, texture), the mapping task could be carried out by matching object attributes alone (object correspondence), rather than by matching locations (relational correspondence).

To investigate whether children can use relational correspondence in mapping, researchers designed map tasks in which information about object features is not sufficient for identifying the target location. Spatial layouts used in these tasks either contain multiple identical objects[56] or open spaces.[15] In these situations, children must rely on spatial cues, such as distance or direction, which allow for distinguishing identical objects or determining a specific location within an open space. Findings generally indicate that preschoolers have more difficulty with these tasks compared to those that can be solved by matching object features.[58,56]

The earliest use of distance in mapping was demonstrated with a task in which children had to locate an object in a sandbox using a picture of the sandbox with a dot marking the object's location.[15] Results showed that 4 year olds were able to translate the distance presented in the picture to the distance in the sandbox. Although these results suggest that the ability to use distance in mapping location emerges almost a year after the ability to use object correspondence, it may still appear surprising that preschoolers can translate distances between spaces of different sizes. However, this early scaling ability may share particular features with the coding of relative extent seen in younger children.[45,61] Duffy and colleagues[61] showed that toddlers coded the height of an object relative to the container in which it was presented. In a mapping task, the frame of a map can be thought of as a container and the outline of the referent space as another container. The early use of distance in map tasks may rely on relative, rather than absolute, coding, allowing children to identify the same relative distance on the map and referent space.

To locate objects based on the information presented on maps, distance cues are not always sufficient. A full characterization of location may require considering angular relations and direction (left/right), in addition to distance. Recent studies examined the early ability to use these types of spatial relations in mapping.[62,63] Shusterman and colleagues[62] found that 4 year olds used distance cues from a map to differentiate locations in the referent space, but failed to use angle and direction. Spelke et al.[63] showed that a year later children successfully used angular relations. However, 5–6 year olds in the latter study failed to transfer directional cues from the map to the referent space, confusing the target object, which had the long side to the left of the short side, with its mirror image. This contrasts with the ability of much younger children to use the same type of cues in spatial reorientation tasks. The failure to use directional information presented on the map may reflect a lack of sensitivity to left/right orientation in 2D pictures. It may also reflect the difficulty of transforming directional cues presented in a 2D picture located in front of the child into a sense of direction in a surrounding 3D space.

The fact that the early ability to use distance and angles in mapping appears prior to any formal instruction in map use indicates that children spontaneously combine their emerging symbolic reasoning with the understanding of spatial relations. It should be noted, although, that this early ability is quite limited. Studies demonstrating the mapping of spatial relations in preschoolers and kindergarteners used simple and small referent spaces. When working with maps representing more realistic and complex environments, young children often focus on salient landmarks and disregard relevant relational information.[58] Through elementary school, children presented with maps of larger realistic spaces have difficulty using distance and angles when the map and the referent space are unaligned.[64] Furthermore, the accuracy of mapping decreases dramatically as the size of the referent space increases,[47] especially when the map represents a large-scale space not perceivable from a single vantage point.[65]

In sum, the ability to solve mapping tasks on the basis of object correspondence appears at 2.5–3 years of age,[60] but the ability to use spatial relations in mapping emerges later and initially manifests itself only in limited contexts. At 4 years, children start using distance cues,[15] and at 5–6 years, they can use angular relations in simple map tasks.[63] During subsequent development in elementary school years, children extend the range of contexts in which they rely on relational correspondence to solve map tasks. They show increased accuracy in mapping spatial relations on tasks involving configurations of multiple objects, a mix of landmark and geometric information, and unaligned spaces. At the end of elementary school, mapping skills further extend to incorporate reasoning about large geographic spaces.[66]

Accumulating experience with maps has important implications for the development of spatial cognition, particularly for thinking about large-scale spaces.[67,68] One of the key features of maps is that they simultaneously represent multiple locations that often cannot be perceived at once through direct experience. Using a map provides children with an opportunity to think about the multiple relations between different locations, much as these relations are captured in the actual maps. Thus, maps provide a structure that can be mentally imposed on a space in thinking about its overall shape, its constituent elements, and the relations among these elements.

BIOLOGICAL AND EXPERIENTIAL FACTORS IN SPATIAL DEVELOPMENT

In addressing issues that are unique to spatial cognition, developmental studies contribute to a more general discussion of the biological and experiential factors involved in the developmental process. When discussing the origins of spatial cognition, some researchers point to findings of impressive spatial abilities in infants, making a case for innate knowledge of critical properties of space.[69,70] Others point to significant limitations of early spatial skills and a gradual growth of competence following particular types of experience in the spatial domain.[71] Given the present state of knowledge, Newcombe[72] has argued for an interactionist approach that acknowledges strong starting points and seeks to identify specific mechanisms implicated in the transformation of early abilities into mature competence. We would further advocate for an approach to understanding the mechanisms of spatial development that attempts to account for the interactions between specific maturational changes and specific environmental experiences. Existing research implicates both biological and environmental processes in age-related changes. Yet little effort has been made to understand how these processes influence each other at different ages throughout development.

With respect to biological factors, many observed improvements in spatial functioning have been associated with the maturation of specific brain regions. For example, increases in the durability of location memory between 18 and 24 months of age may be, at least partly, supported by changes in hippocampal development, and the place learning function of the hippocampus in particular.[73] The subsequent improvement of spatial performance that occurs around 4–5 years—when children become less constrained by particular task features, such as the size of the space—may be related to a further development of this critical region of the brain. Specifically, the growth of the hippocampus-mediated ability to encode relations among multiple objects may lead to an increase in the range of stimuli that children rely on during reorientation and navigation tasks.[74]

Advances in children's spatial performance are also associated with experiential factors. In particular, the emergence of allocentric coding coincides with the beginning of self-locomotion, and subsequent changes in the use of allocentric frames of reference occur as children acquire experience navigating and exploring diverse physical environments. This type of experience may facilitate the ability to locate objects based on their relation to external features of the environment and increase children's sensitivity to features that are perceived as more reliable.[27] Increases in independent mobility and later more specialized experiences may themselves lead to biological changes, such as stimulating hippocampal development.[75] Future research should consider how such bidirectional interactions might affect general spatial development as well as lead to specific individual differences.

CONCLUSION

Research on spatial development reveals impressive abilities in young children. Toddlers and infants show sensitivity to metric information, such as distance, angles, and direction. Children's performance demonstrates their use of the allocentric framework, as seen in their coding of landmarks as cues to object location, and the egocentric framework, as seen in dead reckoning when they update their relation to the target location as they move. Disorientation tasks reveal toddlers' ability to use the geometry of space or more general scalar properties in locating objects. Taken together, these findings clearly indicate that the early points of spatial development are stronger than those posited by Piaget. At the same time, the research shows limitations of early spatial behaviors, suggesting a long developmental progression between early starting points and more mature spatial competence. The use of distal landmarks, for example, undergoes development through elementary school age. During this period, children become progressively more accurate and flexible in their landmark use; they begin integrating their knowledge of individual landmarks to represent relations among multiple locations and to form routes that connect ordered sequences of landmarks. Substantial developments are also seen in the use of the hierarchical coding system—it becomes more differentiated with age and its use extends to a wider range of stimuli and contexts.

More generally, older children become more systematic in the use of spatial information. While younger children demonstrate advanced spatial reasoning in certain contexts, they often revert to more primitive strategies (e.g., coding location only in terms of adjacent landmarks or relying solely on the egocentric frame of reference) in challenging situations, particularly when there is a conflict between different kinds of spatial cues. Older children, however, show a greater resilience in response to conflicting cues and an improved ability to transfer information from one spatial context to another, as seen in their performance on map tasks. Investigators have proposed that some of the observed developments during childhood may reflect the maturation of brain regions implicated in spatial reasoning. Other age-related changes may result from accumulating experience, which, in turn, may further affect neural processing. Much of the experience relevant to spatial development involves interactions with objects in the physical world, which are typical for most children around the world. Other experiences are culture-specific, including learning conventional spatial tools, such as measurement, and acquiring information about symbolic spatial representations, such as maps and models. Still, more work is needed to better understand interactions between biological and environmental factors involved in the development of spatial reasoning. This type of research will allow for a more nuanced characterization of the developmental mechanisms underlying spatial cognition.

ACKNOWLEDGMENTS

This work was supported by a grant from NICHD (#HD059993) and a Scholars Award from the John Merck Fund to SFL.

REFERENCES

1. Kozhevnikov M, Motes MA, Hegarty M. Spatial visualization in physics problem solving. *Cogn Sci* 2007, 31:549–579.
2. Committee on Support for Thinking Spatially. *Learning to Think Spatially: GIS as a Support System in the K-12 Curriculum*. Washington, DC: National Academies Press; 2006.
3. Shea DL, Lubinski D, Benbow CP. Importance of assessing spatial ability in intellectually talented adolescents: a 20-year longitudinal study. *J Educ Psychol* 2001, 93:604–614.
4. Piaget J, Inhelder B. *The Child's Conception of Space*. New York: Norton; 1967.
5. Newcombe NS, Huttenlocher J. *Making Space: The Development of Spatial Representation and Reasoning*. Cambridge, MA: The MIT Press; 2000.
6. Acredolo LP, Evans D. Developmental changes in the effects of landmarks on infant spatial behavior. *Dev Psychol* 1980, 16:312–318.
7. Crowther HL, Lew AR, Whitaker CJ. The development of beacon use for spatial orientation in 6-8.5-month-old infants. *Infant Behav Dev* 2000, 23:1–5

8. Lew AR, Bremner JG, Lefkovitch LP. The development of relational landmark use in 6-12 month old infants in a spatial orientation task. *Child Dev* 2000, 71:1179–1190.
9. Tyler D, McKenzie BE. Spatial updating and training effects in the first year of human infancy. *J Exp Child Psychol* 1990, 50:445–461.
10. Schmuckler MA, Tasng-Tong HY. The role of visual and body movement information in infant search. *Dev Psychol* 2000, 36:499–510.
11. Landau B, Spelke E. Geometric complexity and object search in infancy. *Dev Psychol* 1988, 24:512–521.
12. Rieser JJ, Heiman ML. Spatial self-reference systems and shortest-route behavior in toddlers. *Child Dev* 1982, 53:524–533.
13. Newcombe NS, Huttenlocher J, Drummey AB, Wiley JG. The development of spatial location coding: Place learning and dead reckoning in the second and third years. *Cogn Dev* 1998, 13:185–200.
14. Huttenlocher J, Newcombe N, Sandberg EH. The coding of spatial location in young children. *Cogn Psychol* 1994, 27:115–148.
15. Huttenlocher J, Newcombe N, Vasilyeva M. Spatial scaling in young children. *Psychol Sci* 1999, 10:393–398.
16. Hermer L, Spelke E. A geometric process for spatial reorientation in young children. *Nature* 1994, 370: 57–59.
17. Hermer L, Spelke E. Modularity and development: a case of spatial reorientation. *Cognition* 1996, 61:195–232.
18. Cheng K. A purely geometric module in the rat's spatial representation. *Cognition* 1986, 23:140–178.
19. Huttenlocher J, Vasilyeva M. How toddlers represent enclosed spaces. *Cogn Sci* 2003, 27:749–766.
20. Hupbach A, Nadel L. Reorientation in a rhombic environment: no evidence for an encapsulated geometric module. *Cogn Dev* 2005, 20:279–302.
21. Newcombe NS, Ratliff KR, Shallcross WL, Twyman A. Is cognitive modularity necessary in an evolutionary account of development? In: Tommasi L, Peterson MA, Nadel L, eds. *Cognitive Biology: Evolutionary and Developmental Perspectives on Mind, Brain, and Behavior*. Cambridge, MA: MIT Press; 2009, 107–126.
22. Learmonth AE, Nadel L, Newcombe NS. Children's use of landmarks: Implications for modularity theory. *Psychol Sci* 2002, 13:337–341.
23. Lourenco SF, Huttenlocher J, Vasilyeva M. Toddlers' representations of space. *Psychol Sci* 2005, 16:255–259.
24. Lee SA, Spelke ES. A modular geometric mechanism for reorientation in children. *Cogn Psychol* 2010, 61:152–176.
25. Lee SA, Shusterman A, Spelke ES. Reorientation and landmark-guided search by young children: evidence for two systems. *Psychol Sci* 2006, 17:577–582.
26. Newcombe NS, Huttenlocher J. Development of spatial cognition. In: Kuhn D, Siegler RS, Damon W, Lerner R, eds. *Handbook of Child Psychology*. Hoboken, NJ: John Wiley & Sons Inc; 2006, 734–776.
27. Newcombe NS, Ratliff KR. Explaining the development of spatial reorientation: Modularity-plus-language versus the emergence of adaptive combination. In: Plumert J, Spencer J, eds. *The Emerging Spatial Mind*. New York: Oxford University Press; 2007.
28. Huttenlocher J, Lourenco SF. Coding location in enclosed spaces: Is geometry the principle? *Dev Sci* 2007, 10:741–746.
29. Lourenco SF, Addy D, Huttenlocher J. Location representation in enclosed spaces: What type of information afford young children an advantage? *J Exp Child Psychol* 2009, 104:313–325.
30. Nardini M, Thomas RL, Knowland V, Braddick O, Atkinson J. A viewpoint-independent process for spatial reorientation. *Cognition* 2009, 112:241–248.
31. Hermer-Vasquez L, Spelke ES, Katsnelson AS. Sources of flexibility in human cognition: dual-task studies of space and language. *Cogn Psychol* 1999, 39:3–36.
32. Nardini M, Jones P, Bedford R, Braddick O. Development of cue integration in human navigation. *Curr Biol* 2008, 18:689–693.
33. Baillargeon R, Spelke ES, Wasserman S. Object-permanence in 5-month-old infants. *Cognition* 1985, 20:191–208.
34. Quinn PC. The categorization of above and below spatial relations by young infants. *Child Dev* 1994, 65:58–69.
35. Quinn PC, Adams A, Kennedy E, Shettler L, Wasnik A. Development of an abstract category representation for the spatial relation *between* in 6- to 10-month-old infants. *Dev Psychol* 2003, 39:151–163.
36. Quinn PC, Norris CM, Pasko R, Schmader TM, Mash C. Formation of categorical representation for the spatial relation *between* by 6- to 7-month-old infants. *Vis Cogn* 199, 6:569–585.
37. Baillargeon R. Reasoning about the height and location of a hidden object in 4.5- and 6.5-month-old infants. *Cognition* 1991, 38:13–42.
38. Cohen LB, Younger BA. Infant perception of angular relations. *Infant Behav Dev* 1984, 7:37–47.
39. Lourenco SF, Huttenlocher J. The representation of geometric cues in infancy. *Infancy* 2008, 13:103–127.
40. Slater A, Mattock A, Brown E, Bremner JG. Form perception at birth: Cohen and Younger (1984) revisited. *J Exp Child Psychol* 1991, 51:395–406.
41. Newcombe NS, Huttenlocher J, Learmonth A. Infants' coding of location in continuous space. *Infant Behav Dev* 1999, 22:483–510.

42. Goswami U. *Cognitive Development: The Learning Brain*. New York: Psychology Press; 2008.
43. Haith MM. Who put the cog in infant cognition? Is rich interpretation too costly? *Infant Behav Dev* 1998, 21:167–179.
44. Bushnell EW, McKenzie BE, Lawrence DA, Connell S. The spatial coding strategies of one-year-old infants in a locomotor search task. *Child Dev* 1995, 66:937–958.
45. Huttenlocher J, Duffy S, Levine S. Infants and toddlers discriminate amount: Are they measuring? *Psychol Sci* 2002, 13:244–249.
46. Jeong Y, Levine SC, Huttenlocher J. The development of proportional reasoning: effect of continuous versus discrete quantities. *J Cogn Dev* 2007, 8:237–256.
47. Vasilyeva M, Huttenlocher J. Early development of scaling ability. *Dev Psychol* 2004, 40:682–690.
48. Sandberg EH, Huttenlocher J, Newcombe N. The development of hierarchical representation of two-dimensional space. *Child Dev* 1996, 67:721–739.
49. Plumert JM, Hund AM. The development of memory for location: What role do spatial prototypes play? *Child Dev* 2001, 72:370–384.
50. Vasilyeva M, Duffy S, Huttenlocher J. Developmental changes in the use of absolute and relative information: the case of spatial extent. *J Cogn Dev* 2007, 8:455–471.
51. Plumert JM, Hund AM, Recker KM. Organism-environment interaction in spatial development: explaining categorical bias in memory for location. In: Plumert J, Spencer J, eds. *The Emerging Spatial Mind*. New York: Oxford University Press; 2007, 25–52.
52. Huttenlocher J, Hedges LV, Duncan S. Categories and particulars: Prototype effects in estimating spatial location. *Psychol Rev* 1991, 98:352–376.
53. Leplow B, Lehnung M, Pohl J, Herzog A, Ferstl R, Mehdorn M. Navigational place learning in children and young adults as assessed with a standardized locomotor search task. *Br J Psychol* 2003, 94:299–317.
54. Overman WH, Pate BJ, Moore K, Peuster A. Ontogeny of place learning in children as measured in the radial arm maze, Morris search task, and open field task. *Behav Neurosci* 1996, 110:1205–1228.
55. Rieser JJ, Rider EA. Young children's spatial orientation with respect to multiple targets when walking without vision. *Dev Psychol* 1991, 27:97–107.
56. Blades M, Spencer C. The development of children's ability to use spatial representations. In: Reese HW, ed. *Advances in Child Development and Behavior*. New York: Academic Press; 1994, 157–199.
57. O'Keefe J. The hippocampal cognitive map and navigational strategies. In: Paillard J, ed. *Brain and Space*. New York: Oxford University Press; 1991, 273–295.
58. Liben L, Yekel C. Preschoolers' understanding of plan and oblique maps: the role of geometric and representational correspondence. *Child Development* 1996, 67:2780–2796.
59. DeLoache JS. Young children's understanding of the correspondence between a scale model and a larger space. *Cogn Dev* 1989, 4:121–139.
60. DeLoache JS. Early symbol understanding and use. In: Medin DL, ed. *The Psychology of Learning and Motivation: Advances on Theory and Research*. New York: Academic Press; 1995, 65–114.
61. Duffy S, Huttenlocher J, Levine S. It's all relative: How young children encode extent. *J Cogn Dev* 2005, 6:51–63.
62. Shusterman AB, Lee SA, Spelke ES. Young children's spontaneous use of geometry in maps. *Dev Sci* 2008, 11:1–7.
63. Spelke ES, Gilmore CK, McCarthy S. Kindergarten children's sensitivity to geometry in maps. *Dev Sci* 2001, 14:809–821.
64. Liben LS, Downs RM. Understanding person-space-map relations: cartographic and developmental perspectives. *Dev Psychol* 1993, 29:739–752.
65. Davis C, Uttal DH. Map use and development of spatial cognition. In: Plumert J, Spencer J, eds. *The Emerging Spatial Mind*. New York: Oxford University Press; 2007, 219–247.
66. Downs RM, Liben LS. The development of expertise in geography: a cognitive-developmental approach to geographic education. *Ann Assoc Am Geogr* 1991, 8:304–327.
67. Liben LS. Map use and the development of spatial cognition: seeing the bigger picture. *Dev Sci* 2000, 3:270–274.
68. Uttal DH. Seeing the big picture: map use and the development of spatial cognition. *Dev Sci* 2000, 3:247–286.
69. Spelke ES, Newport EL. Nativism, empricism, and the growth of knowledge. In: Lerner RM, ed. *Handbook of Child Psychology*. New York: John Wiley; 1998, 275–340.
70. Spelke ES, Lee SA, Izard V. Beyond core knowledge: Natural geometry. *Cogn Sci* 2010, 34:863–884.
71. Liben LS. Spatial development in childhood: Where are we now? In: Goswami U, ed. *Blackwell Handbook of Childhood Cognitive Development*. Malden, MA: Blackwell Publishing; 2002, 326–348.
72. Newcombe NS. The nativist-empiricist controversy in the context of recent research on spatial and quantitative development. *Psychol Sci* 2002, 13:395–401.
73. Sluzenski J, Newcombe NS, Satlow E. Knowing where thing are in the second year of life: implications for hippocampal development. *J Cogn Neurosci: Spec Issue Dev Cogn Neurosci* 2004, 16:1443–1451.
74. Sutton JE, Joanisse MF, Newcombe NS. Spinning in the scanner: neural correlates of virtual reorientation. *J Exp Psychol Learn Mem Cogn* 2010, 36:1097–1107.
75. Woollett K, Maguire EA. Acquiring "the knowledge" of London's layout drives structural brain changes. *Curr Biol* 2011, 21:2109–2114. doi: http://dx.doi.org/10.1016/j.cub.2011.11.018.

FURTHER READING

Baillargeon R. Young infants' reasoning about the physical and spatial properties of a hidden object. *Cogn Dev* 1987, 2:179–200.

Bryant P. *Perception and Understanding in Young Children: An Experimental Approach*. New York: Basic Books; 1974.

Cheng K. Whither geometry? Troubles of the geometric module. *Trends Cogn Sci* 2008, 12:355–3610.

Cheng K, Newcombe N. Is there a geometric module for spatial orientation? Squaring theory and evidence. *Psychon Bull Rev* 2005, 12:1–23.

Hund AM, Plumert JM. The stability and flexibility of spatial categories. *Cogn Psychol* 2005, 50: 1–44.

Lee SA, Spelke ES. Two systems of spatial representation underlying navigation. *Exp Brain Res* 2010, 206:179–188.

Loomis JM, Klatzky RL, Golledge RG, Cicinelli JG, Pelligrino JW, Fry PA. Nonvisual navigation by blind and sighted: assessment of path integration ability. *J Exp Psychol Gen* 1993, 122:73–91.

Plumert J, Spencer J, eds. *The Emerging Spatial Mind*. New York: Oxford University Press; 2007.