CHAPTER 9
How Children Learn to Discover Their Environment: An Embodied Dynamic Systems Perspective on the Development of Spatial Cognition
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In the first few years of life, human infants evolve from helpless creatures that are totally dependent on others around them into walking and talking preschoolers. Just after birth, infants have merely relatively immature perception and action systems to learn about the world around them. Yet, by the time they enter school, children have mastered many important skills within the domain of spatial cognition already. They have a good understanding of spatial relations between objects and, between objects and people; they can use spatial language, such as the words “in,” “under,” and “above”; they can navigate and remember the routes they most frequently use in their neighborhood; and they can remember where they have hidden their favorite toy in their bedroom. The speed at which these functions develop, only in a couple of years’ time, has amazed cognitive psychologists, parents, and professionals working with children for a long time. In one of his books, the Flemish author Bernard Dewulf (2011, p. 7) wrote an almost poetic description of the development of his own baby son in this regard (loosely translated here):

He is not able to sit yet. Not completely. For a little while longer, he prefers to sit inside himself, which is easier than on that chair. But on that chair he can do things that he is unable to do otherwise. That’s why he sits inside himself on that chair. With his arms, which he found on himself yesterday, he can reach twenty centimetres further into his expanding room-universe. And if his rubber back allows, he manages to get twice as far. Whatever is beyond, the milky way of the milk bottle, he cries towards himself.
Knowingly or unknowingly, Dewulf’s accurate description touches upon some of the grand theories that developmental psychologists have been working on in the past decades to try and explain the mysteries of child development, including the development of spatial cognition. These theories do not just ask which developmental milestones occur at which age, but rather, they ask how development proceeds. What are the driving forces behind all these major developmental changes that we observe in the first few years of life? One of these theories is known as the theory of embodied cognition, which is part of the larger group of dynamic systems theories and the perception—action approach to development. One of their major premises, touched upon by Dewulf, is that advances in children’s motor development lead to changes in the way children can explore the world. Through exploration, children get new information about the world around them, which in turn elicits new actions and allows them to learn about objects, people, language, and places. These ongoing perception—action cycles are what drives development (see Gibson, 1988; Thelen & Smith, 1996). This chapter first provides an overview of dynamic systems theory, before moving on to a focus on the embodied cognition and perception—action theories. Subsequently, we discuss studies into the development of spatial cognition, which are based on these theories, with a specific focus on mental rotation and spatial memory (including memory for object locations, orientation, and navigation). A number of important questions are addressed such as if, and if so, how, motor development and exploration are related to these different aspects of spatial cognition. Furthermore, if motor development and exploration are indeed related to mental rotation and spatial memory, are such relations restricted to infancy? Is there any evidence that such relations may be causal? To illustrate the challenges associated with developmental research in this area, a section on methods is included. Moreover, sections on clinical groups are presented to describe selected aspects of the development of spatial cognition in children with autism spectrum disorder (ASD), cerebral palsy (CP), and Nonverbal Learning Disability (NLD). The chapter ends with challenges and future directions in this field of research.

9.1 DYNAMIC SYSTEMS THEORY

We begin with an overview of the dynamic systems theory, which is the broader theory under which the embodied cognition approach falls.
Dynamic systems theory, which originally stems from physics, chemistry, and mathematics, was taken over by biology researchers studying the complex dynamics that occur in the natural world, and has found its application in developmental psychology toward the end of the 20th century (Thelen & Smith, 1996). Its major premise is that the developing infant and child can be seen as a complex dynamic system, in which multiple internal and external influences continuously interact (Smith & Thelen, 2003). Within this model, no specific factor, such as biological maturation, is seen as the single cause for driving developmental change. Rather, development is thought to occur as a function of a process called “self-organization.” In the process of self-organization, new structures form and previous ones dissolve through the continuous interactions between the individual parts of the system. Resulting new structures may seem to follow complex rules, but, according to dynamic systems theorists, there are no such higher order organizational principles. In his book on dynamic systems, Kelso (1997, p. 8) describes the concept of self-organization as follows: “(...) spontaneous pattern formation is exactly what we mean by self-organization: the system organizes itself, but there is no ‘self’, no agent inside the system doing the organizing.” Thus, the individual parts of the system together make up a larger, more complex, and coherent whole. As Thelen and Smith (1996) describe it: “These emergent organizations are totally different from the elements that constitute the system, and the patterns cannot be predicted solely from the characteristics of the individual elements” (p. 54). What, then, does this tell us about the developing infant? If we view the infant as the system itself, which shows complex behavior, how do changes in this behavior come about?

The answer to this question is that changes in the systems’ complexity occur as a function of any small change in the individual components that the system is made up of. An often-used example to illustrate this principle is the following. Consider a campus with paved paths and green fields in between university buildings. If the shortest path between two buildings is cutting directly through the grass, then likely, over time, a new path will appear. At first one student will cross along the shortest route, then a few more, and suddenly all students will take this route which is now visible as a clear path. This is the principle of self-organization at work: something seemingly complex emerges through a single small change in the system (the one student taking the shortest route), which leads to a cascade of effects (all the other students who follow his or her path which becomes increasingly visible). Another example, from the field of spatial
development, is the way behavior comes about in infants during a visuospatial working memory task. In this task, the classical A-not-B task (Piaget, 1954), infants are presented with two identical wells that are carved out in the table in front of them. In one of these wells, a toy is hidden while the infant is watching, and subsequently both wells are covered with a cloth. The infant is then distracted from looking at the wells for a few seconds, before being asked to find the toy (see Fig. 9.1). If the infant reaches correctly toward the hiding location, the toy is hidden there again. This first hiding location is called the “A” location. After two correct reaches to this location, the toy is hidden in the other, “B” location. Despite the fact that the infant has seen how the object was hidden in the new location, B, after a short delay infants often reach back to the first location, A. This effect occurs because the infant has formed a habit of reaching to A, and this habit is a stronger determinant of their subsequent action than the new visual input they received when watching the toy being hidden at B (Thelen, Schöner, Scheier, & Smith, 2001). Infants make this error until they reach the age of about 12 months, after which they can normally pass this task in its classical form (Wellman, Cross, & Bartsch, 1986). However, this story is much more complex than it may

Figure 9.1 A-not-B task setup, in which the infant has to remember in which of two wells a toy is hidden. Reprinted from Van de Weijer-Bergsma, E. (2009). Developmental trajectories of attention and executive functioning in infants born preterm: The influence of perinatal risk factors and maternal interactive styles (PhD thesis). Available from NARCIS.
seem at first. Decades of experimental research have shown that there is actually no set age at which infants can pass this task; rather, passing or failing is a function of all specifics of the perceptual input generated by the task environment and the child’s previous experiences (Thelen et al., 2001). For example, Smith, Thelen, Titzer, and McLin (1999) have shown that the child’s position is one of the many determinants influencing task performance. They altered the child’s position between the last reach toward the A location and hiding the toy at the B location for the first time, by moving the child out of a seated position to a standing position on their parents’ lap. In this experimental condition, 10-month-old infants suddenly no longer make the A-not-B error. Thus, the new position somehow disrupts the strong tendency, or habit, to reach toward the A location, illustrating how any small change in the interaction between child and environment can generate novel, seemingly complex, behavior, namely passing the visuospatial working memory task.

In addition to the concept of self-organization, the notion that development occurs across multiple nested timescales is central to dynamic systems theory. The changes that can be observed across, for example, the first few years of life, are ultimately the result of much smaller changes occurring during second-by-second interactions between the child and its environment that take place every day. This focus on nested timescales and microgenetic changes leading to larger developmental changes over time in dynamic systems theory, provides a different view on a typical and widely discussed problem occurring with more traditional so-called “stage theories” of child development. In the traditional stage theories, development is viewed as a succession of stages of increasing complexity. Novel behaviors are acquired quite abruptly; they emerge at once because the child has suddenly grasped a new understanding or skill. However, this suddenness of development is rarely seen in real life. For example, there is a point in the first 2 years of life when all healthy infants learn to walk. From a stage-like view of child development, the infant either can walk already or does not walk yet; there is no in-between. However, when very detailed observations of infant’s behavior are conducted, it becomes clear that this is not how development actually occurs. True, most infants will take their first steps at some point, but this does not mean they will walk wherever they want to go thereafter. Rather, after they have taken their first steps, most infants will revert back to crawling, before they again take a few steps, and then a few more, and so onward, until they use walking as their main way of self-locomotion (Adolph, Robinson, Young, & Gill-Alvarez, 2008; for a detailed review of the huge
amount of natural variability occurring in the acquisition of independent
mobility, see also Adolph & Robinson, 2013). These temporary regressions
to a previous “stage” accompanied with temporary progressions to a more
advanced “stage” are seen as noise in traditional theories. However, in reality,
this intraindividual variability is the rule rather than the exception. Dynamic
systems theory offers an alternative perspective on this issue. Development
across stages occurs only when one looks at the bigger scale of time (Adolph
& Robinson, 2013; Thelen & Smith, 1996). At the microscale temporary
regressions and progressions are perfectly logical, and stem from the ever-
changing conditions in children and their environment. For example,
Corbetta and Bojczyk (2002) investigated infants’ reaching responses before,
while, and after they had learned to walk. In particular, the authors assessed
whether infants reached to objects with one or two hands. During the first
year of life, children usually progress from reaching with two hands without
adapting to the properties of the objects to more adaptive reaching using one
hand for small objects and two hands for larger objects. In the study of
Corbetta and Bojczyk, before the onset of walking, infants indeed tended to
reach adaptively as would be expected. However, in the process of learning
to walk, infants started to reach with two hands to smaller objects as well,
thus showing a temporary regression in their reaching skill. After having
gained sufficient experience with walking and balance control, infants’
increasingly reached to smaller objects with one hand again, showing the
same adaptive behavioral pattern that they had already shown before learning
to walk. Thus, the developing system is constantly reorganizing, and devel-
opment is infinitely more complex than stage theories suggest. It is this com-
plexity and variability that is seen as one of the major characteristics of child
development in dynamic systems theory.

To summarize, in dynamic systems theory, development is seen as a
process of self-organization in which, as Smith and Thelen (2003, p. 344)
put it, “no single element has causal priority.” Rather, new behaviors and
skills emerge as a function of the interactions between the child and its
environment, and relatively small changes in these interactions can offset
reorganization of the developing system, leading to developmental change
over time (Smith & Thelen, 2003).

9.2 EMBODIED COGNITION THEORY

Within the broad theory of dynamic systems, embodied cognition theory
is particularly important to consider for understanding the development
of spatial cognition in infants and children. Previous theories of human cognition have focused on abstract mental representations, in which sensory and motor systems serve the purpose of delivering input and output to and from the cognitive system (Wilson, 2002). In this approach to human cognition, the computer metaphor is often used: the human mind functions just like a computer, with input, output, and a set of computations in between. In contrast, in the embodied cognition approach, sensory and motor systems are seen as fundamentally integrated with cognitive processing. The philosopher Larry Shapiro gives a good example of the distinction between the traditional approach, which uses the computer analogy to cognition, and the embodied cognition approach. In this example, a psychologist is depicted who gives a particular sensory code as input to an organism’s nervous system in the laboratory, resulting in a given set of cognitive processes. Had the psychologist given the same code to the same organism walking about in the outside world, would the cognitive processes be the same? From the traditional cognitive psychology approach, the answer would be “yes”; as the input to the neural system is the same, so will be the output. From the embodied cognition approach, the answer would clearly be “no,” because cognition in this account is viewed as occurring in constant and direct interaction with the environment (Shapiro, 2007). Thelen (2000, adapted from Chiel & Beer, 1997) provides a clear schematic overview of this theoretical account and the way it contrasts to the view of a decoupled environment, body, and brain, which is shown in Fig. 9.2.

What does embodied cognition theory tell us about the process through which children acquire spatial knowledge and understanding? The answers given by the embodied cognition approach are rooted in the ecological psychology approach to development. The ecological psychologist Eleanor Gibson proposed that infants learn increasingly more about the world around them through active exploration. Through exploration, infants learn about “affordances” which are the possibilities for action that occur in the environment (Gibson, 1988; Gibson, 1979). For example, a cup offers the affordance of drinking, a bike offers the affordance of cycling. Clearly, these affordances are not the same for all organisms: for a bird, a bike does not offer the affordance of cycling, but instead may offer the affordance of sitting on (the seat or handlebars) instead. Affordances thus exist in the interaction between agent and environment. Gibson (1988) describes three phases of infant exploration that occur in the first year of life as follows:
1. From birth through 4 months of age, infants explore whatever is nearby enough for them to see, mouth, or touch.

2. Around the age of 5 months, on average, infants learn to reach to objects in their vicinity and manipulate them. This brings about new opportunities for exploration, such as turning, banging, and shaking objects.

3. Around the age of 9 months, on average, infants learn to crawl. With this new skill comes the opportunity to explore a much larger world around them. Not only can infants now seek out objects for exploration which are beyond reaching distance, they also learn to navigate through space independently, allowing them to learn about basic spatial relations between themselves, others, and objects, as well as gain understanding about distance and depth.

Subsequently, in the first half of the second year of life, most infants learn to walk, which again brings about many new opportunities for exploring what is around them. For example, they may learn the
affordance of “transportability” when they start exploring carrying objects from place to place (Gibson, 1988). Subsequently, new phases in exploration may occur through which children can discover other, even more complex affordances (Gibson, 1988). Think, for example, of learning to angle a mirror in such a way that you can see yourself in it or someone standing on the other side of the room, and, a relatively new affordance to learn for children growing up in modern day society, the act of swiping used with technological devices such as smart phones and tablets. Following Eleanor Gibson’s theory, exploration takes a central place in the development of cognition. The way children can explore their environment, in turn, changes with development as a function of advances in visual perception and increasing motor skill, among other factors. For example, with the acquisition of new gross motor skills, such as sitting upright, infants gain access to a whole new array of opportunities to elicit perceptual information from the world around them and discover novel affordances (see also Bernard Dewulfs’ description of his son at the outset of this chapter). Thus, through exploration, infants learn about the properties of the physical and social world around them. With respect to visuospatial cognition, achievement of motor milestones for self-locomotion (i.e., crawling, walking) seems especially important. We will turn to this issue in section 9.3.1

9.3 INTERIM SUMMARY

To summarize, dynamic systems and embodied cognition theory suggest that developmental changes in (spatial) cognition come about through the child’s interactions with his or her environment that occur second-by-second and day-by-day through ongoing perception—action cycles. As infants grow older and learn to sit, crawl, and walk, they are increasingly able to explore the world around them, allowing them to discover new affordances and gain insight in spatial relations. Having briefly explained the general ideas behind dynamic systems and embodied cognition theory, we now turn to the application of these theories to studies of the development of spatial cognition. Landau (2002) defined spatial cognition as “the capacity to discover, mentally transform, and use spatial information about the world to achieve a variety of goals, including navigating through the world, identifying and acting on objects, talking about objects and events, and using explicit symbolic representations such as maps and diagrams to communicate about space” (p. 395). Here, we focus
on the role of infant motor development and exploration in the develop-
ment of two central aspects of spatial cognition touched upon by Landau,
which first emerge in the first years of life: mental rotation and spatial
memory (including memory for object locations, orientation, and naviga-
tion). Although many studies have also investigated other aspects of spatial
cognition from an embodied dynamic systems perspective, such as spatial
language, for reasons of space limitations this is not the focus of the cur-
rent chapter (for further information on the topic of spatial language, see,
eg, Oudgenoeg-Paz, Leseman, & Volman, 2015). For each of the domains
of mental rotation and spatial memory, first, examples of current methods
used with infants and older children are described, followed by a review
of studies looking into how motor development and exploration are
related to these key aspects of spatial cognition.

9.3.1 Mental Rotation

Assessment methods and developmental change. Mental rotation is “the imagined
movement of an object (or array of objects) in 2- or 3-dimensional space”
(Frick, Ferrara, & Newcombe, 2013, p. 117). Various paradigms exist to
assess mental rotation ability in infants and children. In infants, the
violation-of-expectation paradigm is often used in which look duration
toward a stimulus is measured. The central tenet of this paradigm is that
infants will look longer at what is unexpected and novel than to what is
familiar to them. Thus, by familiarizing infants with the stimulus first and
then showing another stimulus that is subtly different, infants’ sensitivity to
these differences can be tested. For example, in studies of mental rotation, as
shown in Fig. 9.3, infants are shown an object which has a different colored
front and back and is asymmetrical in shape (familiarization phase).
Subsequently, the object is rotated behind an occluder and then presented
again (test phase). In the test phase, the object is either the same as the
object in the familiarization phase, but rotated in angle (congruent condi-
tion) or its own mirror image presented at an angle (incongruent condi-
tion). If infants look longer toward the incongruent compared to the
congruent condition, this is taken as evidence for their understanding that
the former is impossible, implying they would have had to use mental rota-
tion to match the objects between the familiarization and test phase (but see
Box 9.1 on methodology). Möhring and Frick (2013) used this paradigm
with 6-month-old infants and showed that under certain conditions,
Stimuli and time course of test events

(A) **Stimulus object**

Front  Back

Original object (180°)

(B) **Video sequence**

Mirror object (45°)

**Figure 9.3** Illustration of infant violation-to-expectation paradigm to test mental rotation. Reprinted from Frick, A., Möhring, W., & Newcombe, N. S. (2014). Development of mental transformation abilities. Trends in Cognitive Sciences, 18(10), 536–542 (Adapted from Frick & Möhring, 2013, and Möhring & Frick, 2013—permission obtained from John Wiley and Sons).

**BOX 9.1 Methodology**

**Studying Cognitive Development—Methodology Matters**

The present chapter is, very deliberately, not focused at describing age-related trends in the development of spatial cognition. In fact, we have tried to stay away from general claims that children at a certain age are able to do X or Y—instead we have aimed to discuss children’s task performance in particular experimental setups at particular ages. The reason behind this choice of focus is not that we do not believe infants and children make large progress in spatial cognitive skills, such as mental rotation, navigation, and memory, over time—clearly, large developmental advances are observed. Instead, in our point of view, such developmental improvements can only be accurately described when different age groups are given exactly the same task, which is only rarely the case across different studies.

To illustrate, consider the section on mental rotation in which we describe how 6-month-old infants seem capable of mentally rotating an object, at least after having been allowed to manually explore the object prior to the task (Continued)
BOX 9.1 Methodology—cont’d
(Möhring & Frick, 2013). In contrast, when Frick et al. (2013) assessed mental rotation using the touch screen task shown in Fig. 9.4 in 3.5- to 5.5-year-old children, they observed that the younger age group (i.e., 3.5–4.5 years) performed quite poorly. How might these differences come about? A close look at the two tasks administered reveals marked differences. First, the response mode is different: whereas infants only had to look at the screen, the preschoolers in the study by Frick et al. (2013) had to integrate looking at the screen while pointing to indicate their response. Keen (2003) studied these differences in task demand between different age groups in another field of cognitive development: children’s knowledge of physical laws of solidity and continuity. The title of her paper nicely summarizes the problem at hand: “Representations of objects and events: Why do infants look so smart and toddlers look so dumb?” Keen describes the exact same phenomena of contradictory results between infant and toddler studies: whereas infants showed signs of having at least rudimentary understanding about object solidity and continuity, as evidenced by their looking behavior in a violation-to-expectation paradigm, toddlers failed to demonstrate such knowledge in a reaching task. However, when toddlers were also given a looking-time task, like infants, they looked longer at the unexpected outcome (Mash, Novak, Berthier, & Keen, 2006). The question as to why pointing and looking responses may produce such different behavioral patterns in young children has been much debated (see, e.g., Thelen et al., 2001). One potential explanation which has received

Figure 9.4 Mental rotation task example used with 3.5- to 5.5-year-olds. In this task, children had to indicate in which of the two holes the figure would fit. Reprinted from Frick, A., Ferrara, K., & Newcombe, N. S. (2013). Using a touch screen paradigm to assess the development of mental rotation between 3½ and 5½ years of age. Cognitive Processing, 14, 117–127. Copyright 2013, reprinted with permission from Springer.

(Continued)
some support is that, in addition to the apparent difference in terms of response mode, there is a more “hidden” difference in requirements between the expectation-to-novelty and reaching tasks: whereas the former present infants with an end-state which they have to judge as either correct or incorrect, the latter asks children to actively predict the outcome themselves (Frick, Möhring, & Newcombe, 2014; Keen, 2003). However, the difference between predicting action outcomes and solely having to judge outcomes that are given does not fully seem to explain the different results obtained from violation-to-expectation paradigms administered to infants and reaching tasks administered to older children. For example, Lee and Kuhlmeier (2013) studied the difference in looking and pointing behavior in 2-year-olds in a physical reasoning task. When asked to predict the task outcome, children’s looking behavior was more frequently correct than their reaching. Similar effects have been observed in the A-not-B task: infants’ correct looking seems to precede correct reaching (Cuevas & Bell, 2010; Diamond, 1985). Thelen et al. (2001) argue for a dynamic systems’ interpretation of these findings, in which looking and reaching behavior should not be seen as separate clues as to what the infant “really” knows or not, but rather, as the result of the complex interaction between the different perceptual inputs and the child’s previous experiences with the task.

To summarize, children’s cognitive task performance relies so strongly on the exact task demands that outcomes of studies that used different paradigms to assess the same cognitive “skill” are very difficult to compare. This general finding fully fits with a dynamic systems theory of cognitive development (Smith & Thelen, 2003). Along these same lines, Acredolo (1990) cautions in her review on spatial orientation in infancy that the fact that infants of a particular age seem to use a nonegocentric strategy to solve a particular orientation task, should not be taken as evidence that infants at that age switch from using egocentric to nonegocentric strategies in general. Rather, as Acredolo states, the (behavioral) patterns “were obtained in a particular paradigm, with a particular environment, and with particular training procedures” (p. 603). For example, as discussed in the section on spatial orientation and navigation in this chapter, the familiarity of the testing environment may strongly influence infants’ response pattern (Acredolo, 1979). What is it that we can learn from these studies then? We can learn about the nature of developmental change within studies using exactly the same paradigm across different age groups, and we can learn that children are able to use strategy X under condition Y at a certain age; this does not mean they will always do so, but it shows something about the expanding behavioral repertoire that they have available from which they may increasingly select the most efficient

(Continued)
BOX 9.1 Methodology—cont’d
strategy, or the strategy with the most proof of success (Siegler, 1996). The developmental picture, then, is far from black and white.

Novel Techniques to Assess Spatial Cognition in Infants and Children
In the past decade, novel techniques have facilitated the study of spatial cognition in infants and children, such as the use of eye tracking and virtual reality tasks. Very recently, the technique of head-mounted eye tracking has been added to researchers’ repertoires for studying development in this domain (Franchak, Kretch, Soska, & Adolph, 2011). A head-mounted eye tracker consists of two very small cameras connected to a lightweight cap, which is placed on the infants’ head (see Fig. 9.5). The first camera points outward and captures what is in the infants’ field of view. The second camera points

detailed further below, infants this young already looked longer at the incongruent outcome compared to the congruent outcome.

In older children, a different task setup to assess mental rotation is often used (eg, Frick et al., 2013; Örnkloo & Von Hofsten, 2007). Frick et al. (2013) used a touch screen design to assess 3.5- to 5.5-year-olds’ mental rotation abilities. Children were shown a display with a figure and two different holes on the screen, and asked to indicate in which of the two holes the figure would fit, as shown in Fig. 9.4. After dividing the sample into two age groups (ie, 3.5—4.5 years and 4.5—5.5 years), Frick et al. (2013) showed that 27% of children in the youngest age group performed well on the task, compared to 46% in the older age group. Good performance was defined as pointing to the correct hole in more than 10 out of 16 trials. Furthermore,
they studied the effect of disparity, or the degree of rotation necessary to fit
the figure into the hole, on task performance. Interestingly, both error rates
and response times significantly increased with increasing disparity in the
older, but not the younger age group. These findings suggest that the chil-
dren in the older age group used mental rotation as a strategy to solve the
task, whereas the younger age group failed to do so effectively. As such,
results seem to conflict with those observed by Frick and colleagues in
infants, who showed signs of being able to mentally rotate an object at a
much younger age. To understand these contradictory results, the specific
methods used and what they exactly require of children should be
considered—an issue further discussed in Box 9.1.

Motor development and exploration in relation to mental rotation. Embodied
dynamic systems theory poses that both motor development and explora-
tion may be important factors in the development of (spatial) cognition.
Thus, having described a number of frequently used measures to assess
mental rotation in infants and children and developmental change in per-
formance on those, we turn to the following question next: is there any
evidence for an association between motor development, exploration, and
mental rotation? In their study using the violation-of-expectation para-
digm with 6-month-old infants, Möhring and Frick (2013) divided
infants into two conditions: those in the manual exploration condition
were given the opportunity to manually explore the object at the outset
of the experiment, in an encoding phase, while those in the observation
condition were only allowed to watch the object during this time. A clear
difference between groups emerged: infants in the manual exploration
condition looked significantly longer at the objects in the incongruent
compared to the congruent condition, while this difference was not
apparent in the observation condition. Thus, the authors conclude that
infants as young as 6 months of age are capable of rudimentary forms of
mental rotation, but only when given the opportunity to manually
explore the object first. This finding fits in well with the dynamic
embodied cognition view described above: exploration experience plays a
crucial role in spatial cognition, mental rotation in this case.

These findings raise the question at what age manual experience with
an object is no longer a prerequisite for mental rotation. Using the same
experimental setup, Frick and Möhring (2013) addressed this question in
8- and 10-month-old infants. Infants were given only visual experience
with the stimulus prior to the experiment. Eight-month-olds showed the
same behavioral pattern as the 6-month-olds without manual exploration
experience in the study by Möhring and Frick (2013): they did not look longer at the incongruent compared to congruent condition, thus showing no signs of being able to mentally rotate the object. However, 10-month-olds clearly distinguished between the two stimulus types in the test phase. The difference was large: whereas only 45% of 8-month-olds looked longer at the incongruent compared to congruent trials in the test phase, this was the case for 90% of the 10-month-olds. These findings may be taken to suggest that manual experience is no longer a prerequisite for mental rotation in 10-month-old infants. However, in order to better understand this effect, we must consider what happens between the age of 8 and 10 months in development: major advances in gross motor development occur during this time, as many infants learn to self-locomote. When studying performance on the mental rotation task in relation to infants’ motor development, a clear pattern emerged: after statistically controlling for age, infant mental rotation ability was significantly related to a number of aspects of gross motor development, such as standing and walking with assistance (note however, that no association with crawling was found after controlling for age) (Frick & Möhring, 2013). The authors conclude that, with increasing experience with self-locomotion, infants’ “reasoning about spatial relations between objects (or objects and agents) may become increasingly independent from their own location and perspective” (Frick & Möhring, 2013, p. 717).

Further evidence for the role of motor development and exploration experience on mental rotation in infants comes from the work of Schwarzer, Freitag, Buckel, and Lofruthe (2013). Schwarzer and colleagues investigated mental rotation abilities in 9-month-old infants with and without crawling experience. After letting infants habituate to a rotating shape, infants were shown six test trials of rotating stimuli: three with the same shape as was used during the habituation phase, and three with its mirror image. The authors showed that infants with crawling experience looked significantly longer toward the unexpected test outcome (i.e., the mirror image shape) than toward the expected test outcome, whereas infant who could not yet crawl, did not. An important question is whether the associations observed between motor development, exploration, and mental rotation ability are restricted to infancy. Recent studies show that this is not the case. For example, Jansen and Heil (2010) found that specific aspects of motor development in 5–to 6-year-olds were associated with mental rotation ability at this age. They included a standardized motor test (the motor development test (MOT),
Zimmer & Volkermar, 1987) to assess coordination ability, fine-motor skills, balance, catching, jumping, speed of movements, and motor control. Their results showed that, after statistically controlling for nonverbal intelligence, motor control was significantly related to mental rotation ability, as assessed using a paper-and-pencil test.

Thus, in infants, having experience with the object itself and manipulating it (ie, exploration), facilitates mental rotation. Also, advances in gross motor development, in particular self-locomotion, allow infants to learn about object properties and spatial relations, facilitating mental rotation. In older children, links between motor control and mental rotation are also observed. Do these findings also fit in with the embodied dynamic systems framework? And if so, how? The answer, we believe, is yes if mental rotation itself is—at least in part—seen as the making of a motor plan which is not executed. This assumption was put to the test by Wexler, Kosslyn, and Berthoz (1998). Wexler and colleagues asked a group of adults to perform a mental rotation task while turning a joystick with their hand. The direction of the joystick turn was either compatible or incompatible with the mental rotation task (ie, clockwise mental and motor rotation or counterclockwise mental rotation and counterclockwise motor rotation). Mental rotation was faster and more accurate in the compatible condition, providing support for the suggestion that mental rotation is closely tied to motor processes. Thus, if children practice making and executing motor plans in general this might facilitate making motor plans which are purely “mental” (and thus not executed) too. From this perspective, it is noteworthy that in the study by Jansen and Heil (2010), many aspects of motor development were studied in relation to mental rotation and only one of them was found to be a significant predictor over and above nonverbal intelligence: motor control. Thus, the precision with which motor plans are practiced may make a difference. Further evidence for this suggestion comes from studies with adults. Moreau, Mansy-Dannay, Clerc, and Guerrién (2011) studied mental rotation ability in athletes with various levels of experience: novices and experts. They showed mental rotation ability was better in expert athletes, but whether this effect was observed depended on the number of hours spent in training and the type of sport assessed. Specifically, the difference in mental rotation ability between novices and experts was apparent in combat sports (fencing, judo, and wrestling) but not in roadrunners. Whereas practicing combat sports requires very precise motor plans in terms of directionality, timing, and force, which need to be adapted all the time to the specific situation, this is not as much the case for roadrunners.
In summary, there is evidence for the relation between motor skill and mental rotation ability, which would be expected based on an embodied cognition perspective. Moreover, this relation is observed throughout development, from infancy through to adulthood. It seems that in particular practice with making and executing precise coordinated motor plans relates to the ability to solve mental rotation tasks. This suggests that, when mentally rotating an object, this may not be much different from imagining the act of rotating the object—something which may not so much be an abstract representation in the brain, but rather much more closely aligned to the act of rotation itself, even if that act is not executed (see Wexler et al., 1998). Studies of the role of exploration on mental rotation to date appear to be restricted to infancy; further research is needed to study if and how exploration relates to mental rotation ability in older children. Next, we turn to another important aspect of spatial cognition: spatial memory.

9.3.2 Spatial Memory: Remembering Locations and Finding One’s Way in the World

Studies of the development of spatial memory ask at what age infants and children are able to memorize nearby and distant (object) locations, and which information infants and children use to guide their memory. A complete literature review of this broad research area falls outside of the scope of this chapter (for comprehensive reviews, see, eg, Cornell & Heth, 2006 for a review on children’s way finding; Campos et al., 2000; Newcombe & Huttenlocher, 2003; Newcombe, Uttal, & Sauter, 2013). Instead, we focus on the key questions raised above, namely how changes in the development of spatial memory relate to motor development and exploration in infants and children, after having described a number of frequently used assessment methods and developmental changes in performance on those. In doing so, we distinguish between studies that have investigated spatial memory in task situations where children remain stationary, from studies in which children move or are moved before they respond.

9.4 Spatial Memory on the Move: Orientation and Navigation

Assessment methods and developmental change. The study of the development of navigation skills to date has focused on the question as to how infants and children are able to orient themselves in the environment. Which cues do children use to reorient themselves after having been moved (younger
children) and how do they find their way (older children)? Studies in this area have addressed developmental changes in the use of egocentric versus allocentric reference systems, and related the use of landmarks. Piaget (1954) already observed that young infants tend not to have an “objective” notion of space, but rather, code object locations only in relation to themselves and their own location. A series of early experimental studies have indeed confirmed that young infants tend to rely strongly on egocentric, rather than allocentric, referencing, while marked changes occur over the first years of life (Acredolo, 1978; Acredolo and Evans, 1980; Newcombe, Huttenlocher, Dummeney, & Wiley, 1998).

The paradigm often used in infant studies is the reorientation task designed by Acredolo (1978). In this task, infants were placed in a chair attached to a round table in the middle of a testing room (see Fig. 9.6). Windows, labeled X and Y, were present on either side of the infant. In the first phase of the experiment, the infant learned that following the sound of a buzzer, an experimenter would appear at window X. After infants demonstrated proof of this principle, as evidenced by their anticipatory looks to window X before the experimenter appeared, he or she was moved to the other side of the table. The buzzer was then rung again, but no one appeared at the window. If the infant used an egocentric referencing strategy, they would be expected to look at window Y; if they did not respond egocentrically, they would be expected to look at window X (see Acredolo, 1978). Using this measure, Acredolo (1978) tested 24 infants longitudinally at age 6, 11, and 16 months, showing clear age-related differences in

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**Figure 9.6** The infant reorientation experiment used by Acredolo (1978). $S_1$ and $S_2$ mark the infants’ location during the training and test phase, respectively. Reproduced from Acredolo, L. P. (1978). Development of spatial orientation in infancy. Developmental Psychology, 14, 224–234. Reprinted with permission from the American Psychological Association.
performance: whereas only 8% of 6-month-olds responded nonegocentrically, this was the case for 33% of 11-month-olds, and 75% of 16-month-olds (the difference between 6 and 16, and 11 and 16 months was significant, the difference between 6 and 11 months was not). In a follow-up study using the same experimental setup, Acredolo and Evans (1980) studied the effect of landmarks and landmark salience on test performance in 6-, 9-, and 11-month-old infants. In a condition with no landmark, the large majority of infants in all age groups responded egocentrically, as in the study by Acredolo (1978). However, infants greatly benefited from the introduction of a salient landmark close to the goal location (i.e., a beacon). Whereas a large percentage of the 9- and 11-month-olds responded correctly in this condition, 6-month-olds gave a much more mixed pattern of results, and were seemingly undecided about which information to use.

One point of critique that has been raised in response to these findings is that there is an alternative likely explanation for the results: the role of motor habit formation (see, e.g., the discussion by various experts in Acredolo’s book chapter, 1990). As evidenced by the many studies on the A-not-B task, young infants tend to form strong motor habits when they are asked to repeat a specific action (i.e., reach to the A location) multiple times and this habit is hard to overcome. In the Acredolo studies, infants were trained to look toward window X (say X is on their left hand side) multiple times before they were turned around the table. After rotation, their motor habit would still be to look toward their left—which is where window Y is now located. To test this alternative explanation, Acredolo (1979) repeated her experiment with two bowls on the table in front of the infant. Infants saw how an object was hidden in the bowl on their left, and were then—without establishing any prior motor habit to reach to either bowl—turned around the table. Crucially, infants—aged 9 months—still mostly responded egocentrically, but only in two of three conditions: egocentric responding dominated when infants were tested in a landmark-free laboratory and in a landmark-filled office, but correct responding dominated when infants were tested in the familiar surroundings of their own home. Thus, these findings confirm that very young infants in a lab situation indeed code object locations in relation to their own location, and the effects in the Acredolo (1978) and Acredolo and Evans (1980) studies cannot be explained by an effect of motor habit only. The role of context (home, lab, office) should not be ignored though—given that both the home and the office contained many landmarks in Acredolo’s experiment (1979), yet infants’ response patterns
were very different, suggests that it may be something to do with the familiarity of the home that facilitates performance. As Acredolo (1979) suggests, perhaps infants are more easily oriented in their own home because they know the spatial layout, or familiar objects are more easily used as landmarks than unfamiliar ones.

To summarize, infants in the first year of life seem to have difficulty reorienting themselves in an unfamiliar environment after they have been moved, although they become increasingly able to use salient landmarks. In her review of spatial orientation in infants, Acredolo (1990) nicely summarizes this finding of the use of predominantly egocentric strategies in early infancy as (infants) “behave as if their body is the pivotal center of space” (p. 597). As they grow older, children become increasingly able to use various types of information for navigation. For example, van den Brink and Janzen (2013) presented children aged 30 and 35 months with a virtual reality scene on a screen where a bird was flying and hiding behind one of two identical trees. Once the bird had disappeared, the camera’s perspective moved to change perspective by 90 degrees. The movement of the camera followed a path mimicking self-motion. Children then had to indicate where the bird was hiding. In order to do this, children had to maintain their perspective during the movement of the camera. This could be done by using the visual spatial cues provided by the optic flow and the objects present in the scene. However, as children were sitting during the task, they could not use cues generated by their own movement (proprioceptive information). Results showed 35-months-olds were able to use these selective visual cues to find the bird, while 30-months-olds were not yet able to do so. In a different study, Newcombe et al. (1998) showed toddlers aged 16–24 months and 28–34 months how a toy was hidden in a sandbox. Subsequently, they walked around the sandbox and were asked to search. The advantage of the sandbox setup is that it allows very fine calibration of children’s errors, as performance can be coded in terms of the distance between the search location and the hiding location, rather than as a cruder pass/fail score. Newcombe and colleagues found that the introduction of distal landmarks improved search performance compared to a condition in which no such landmarks were present in children aged 22 months and older, but not in younger children. Subsequent studies, using a range of different methods, such as the use of touch screens, real mazes, and virtual reality tasks, have confirmed that with increasing age, children become increasingly skilled at using landmarks (Bullens, Iglói, Berthoz, Postma, & Rondi-Reig,
However, this does not imply that a stage-like developmental shift occurs in the use of allocentric over egocentric reference frames. Rather, as Nardini, Burgess, Breckenridge, and Atkinson (2006) found, the use of egocentric and nonegocentric reference frames may operate in parallel already from 3 years of age onward, as has also been found in adults (Nadel & Hardt, 2004; Wang & Spelke, 2002).

Motor development and exploration in relation to spatial orientation and navigation. Having addressed a number of measures that have frequently been used to assess spatial exploration and navigation in infancy and childhood, and developmental improvements in performance on these measures, we next turn to the question if and how motor development and exploration relate to improvements in spatial orientation and navigations skills in child development. To address this question, Acredolo, Adams, and Goodwyn (1984) investigated how self-locomotion and visual tracking during locomotion play a role in performance on a search task in 12- and 18-month-old infants. In their search task, infants were shown how a toy was hidden in one of two wells. From the infants’ position, the toy could not be reached directly. Instead, infants had to move around the display to the opposite end before they could retrieve the toy. If infants relied on a purely egocentric reference system, they would not be able to find the toy in the correct well. Experimental manipulations involved asking infants to move around the display themselves, asking the parent to carry them around, and obscuring the view of the hiding wells from the side of the display, which infants passed during movement. Results showed a clear effect of condition: 12-month-olds who were carried around the display made more errors than those who moved around it themselves. This effect seemed largely due to infants’ visual tracking of the toys’ location during movement, which occurred much more when infants moved around the display themselves than when they were carried. When the clear sidewalls of the display were replaced with opaque ones, so that visual tracking was no longer possible, self-locomoting around the display no longer resulted in improved performance in the 12-month-olds. Interestingly, when the same infants were 18 months of age, the effect of experimental condition on performance disappeared; almost all infants of this age were able to perform the task well, irrespective of the way they moved around the display or the opportunities they had for visual tracking. Van den Brink and Janzen (2013) also demonstrated the link between exploration and spatial skill. They measured toddlers’ skill to maintain
orientation while perspective changes (using a paradigm described earlier) and found that toddlers who were more independent in their daily functioning performed this task better. They hypothesized that toddlers who are more independent have more opportunities for spatial exploration than their peers who are more dependent on their caretakers.

In another study, Hazen (1982) investigated both the role of quantity and mode of exploration in relation to toddlers’ ability to navigate through a playhouse. She concluded that it is the mode of exploration that matters for spatial knowledge, rather than quantity of exploration. The mode of exploration was coded as the degree to which children actively (i.e., they traveled along their own path) or passively (i.e., they were carried by their parents, or parents led them along a certain route) explored the playhouse. These findings match well with those of Acredolo et al. (1984) in showing that locomotion and exploration are important factors in children’s navigation, particularly so if the child is an active agent. Visual tracking, elicited when children self-locomote through the environment, seems to be a key factor explaining these effects. Foreman, Foreman, Cummings, and Owens (1990) found a similar effect with 4- to 6-year-olds who either were being pushed around a maze in a wheelchair or had the opportunity to walk around and actively explore the maze themselves during a training phase. In the subsequent test phase, the latter group outperformed the former at finding hidden sweets in the maze.

If self-locomotion, as opposed to passive locomotion, is such a crucial factor in spatial memory, does the experience infants have with self-locomotion matter for their performance on spatial memory tasks? The evidence indeed suggests that this is the case. Clearfield (2004) studied 8-, 12-, and 14-month-old infants’ search behavior in an octagonal arena with a number of landmarks. After a number of training trials, infants’ mothers were asked to hide behind one of the sidewalls, while infants were carried to another sidewall by the experimenter. Subsequently, infants were encouraged to find their mothers by moving toward them. Performance was studied in relation to the number of weeks of experience children had with crawling and walking, showing strikingly similar results: number of weeks of crawling and walking experience was positively related to task performance. The effect of crawling may be taken to mean that it is infants’ first experience with self-locomotion that propels spatial memory, but the fact that a similar effect was observed for walking suggests that something more is going on: all walking infants in this study...
were expert crawlers and had many weeks of crawling experience. Thus, the key message from this study is that what infants learn apparently does not (or at least not fully) transfer between crawling and walking (see also Adolph, 1997). Clearfield (2004) concluded “This implies that infants’ behaviors in this task may be due to the soft assembly of available perceptual inputs, memory for the spatial location, and locomotor skill” (p. 231). Her explanation comes remarkably close to Thelen and Smith’s account of infant performance on the A-not-B task described at the outset of this chapter: performance comes about through the interaction between child and environment, and any larger or smaller change may drastically alter task performance. In the case of Clearfield’s experiment, the fact that novice walkers performed relatively poorly, despite their extensive experience with crawling, may be explained because walking still requires much attention in novices, which reduces cognitive capacity available for spatial memory. Sarah Berger (2010) tested this assumption directly in a large version of the A-not-B task in which 13-month-old infants were required to move toward their parent on the end of one of two walkways. After having moved through one of the paths a few times toward the A location, the parent moved to the other, B, location. In one of the experimental conditions, two tunnels replaced the two paths that children could take. In this demanding tunnel condition, for walking infants, the extent to which children made perseverative errors was negatively related to walking experience. This study confirms that, indeed, there is a cognition—action trade-off which can impact memory and inhibition performance in infants (Berger, 2010): when the motor demands of a task are high, novice walkers struggle because their attention is largely consumed by the effort needed to just keep walking, thereby reducing task performance.

To conclude, there is substantial evidence to suggest that motor development, in particular experience with self-locomotion, is tied to spatial memory, the use of landmarks, and navigation (see also Campos et al., 2000, for a review on this topic). In particular, children’s self-locomotion through an environment aids navigation because of enhanced visual scanning during self-locomotion compared to passive locomotion (ie, when the child is carried). Further, the more experience children have with a particular form of self-locomotion, such as crawling or walking, the more skilled they become,

1 Note that Thelen and Smith (1996) also use the term “soft assembly” to describe the dynamics of developing cognitive function.
leaving more attentional resources available for spatial memory. In this account, advances in gross motor skill in fact interfere with spatial memory, leaving open the question as to whether motor development may be driving advances in spatial memory. To address this question, we turn to the literature on spatial memory in stationary tasks next. Again, we describe a number of frequently used methods in this field first, as well as developmental changes in performance, before turning to the question as to how spatial memory during such stationary tasks relates to motor development and exploration.

9.5 SPATIAL MEMORY IN STATIONARY TASKS

Assessment and developmental change. One of the most influential tasks in the cognitive developmental literature which taxes children’s memory for object location, among other factors, is the A-not-B task described previously (see section 9.1). Although the A-not-B task has most often been used with infants, older children still make the A-not-B error under specific task conditions. Schutte, Spencer, and Schöner (2003) presented 2-, 4-, and 6-year-olds with a sandbox version of the A-not-B task. The sandbox task requires very fine spatial precision, because no direct cues to the objects’ location are available as in the typical infant version with separate hiding wells. A clear pattern of results emerged in which age effects interacted with the distance between the A and B location: at a large distance, only 2- and 4-year-olds’ responses drifted toward the A location on B trials, and 6-year-olds did not make the A-not-B error. At a very small distance between the A and B location, however, 6-year-olds also made the A-not-B error. This study thus shows that the A-not-B error and its underlying processes are not confined to infancy, and the coding of object locations in spatial memory becomes increasingly precise as children grow older (Schutte et al., 2003).

Another paradigm that has been used to assess spatial memory in children is the memory for location task. In this task, children are asked to remember at which of several hiding locations a toy is hidden. For example, Pelphrey and colleagues (2004) studied 5.5–12.5-month-old-infants’ memory for location in relation to the length of delay between hide and search (range 2–10 seconds) and the number of hiding locations (range two to four). Linear age-related improvements in the ability to cope with delay were observed across the age range studied, while improvements in the number of to-be-remembered locations increased from 8 months onward. In addition to studying the effects of the length of delay and the number of hiding locations present, the number of locations that children can hold in memory
simultaneously has also been of interest. Alloway, Gathercole, and Pickering (2006) investigated the development of memory for location using a Dot Matrix task as part of a larger working memory assessment in children aged 4—11 years of age. Children were shown a four by four grid on the computer screen in which a red dot appeared in 1 of the 16 spaces on the grid, and the sequence of to-be-remembered locations increased as children progressed through the task, showing clear age-related improvements across the age range tested. Thus, with increasing age, children learn to retain an increasing number of locations in short-term memory, and to remember this information over increasingly longer delays and with increasing spatial precision. We next turn to the key question addressed in this chapter: how are self-locomotion, exploration, and spatial memory linked in development?

**Self-locomotion, exploration, and spatial memory performance in stationary tasks.** Campos and colleagues (2000) conducted a review of studies investigating the relation between motor development and A-not-B task performance in infants. Across a number of studies conducted in the 1980s, and across multiple cultures, they conclude that indeed self-locomotion is linked to advances on A-not-B task performance (see, eg, Horobin & Acredolo, 1986). A recurrent debate concerning these findings entails the question as to whether self-locomotion and advances in spatial memory are causally linked in development, or whether this association is due to a shared general developmental factor. In the latter case, children who are ahead of their peers in one developmental domain (such as the development of gross motor skills, including self-locomotion) are ahead of their peers in other domains (such as spatial memory) too, just because they are quick to develop in general. To disentangle these two alternative explanations, Kermoian and Campos (1988) divided a sample of 8.5-month-old infants into three groups: infants with no self-locomotion experience, infants with no self-locomotion experience except for walker-assisted experience, and infants with crawling experience. If the association between self-locomotion onset and spatial cognition was due to a general maturational factor, the walker-assisted group would have to cluster with the groups of infants without self-locomotion experience (ie, walker-assistance can be seen as an artificial aid unrelated to the child’s developmental level). The contrary was true: the children in the walker-assisted group performed at a similar level as the children who could crawl, and both groups scored significantly better than the infants without self-locomotion experience. Thus, self-locomotion indeed seems to facilitate
A-not-B task performance. Campos and colleagues (2000) provide four potential explanations for this association: (1) infants learn to shift from using an egocentric to allocentric reference frame through experience with self-locomotion, (2) self-locomotion experience improves attentional discrimination, (3) self-locomotion experience improves goal-directed behavior and tolerance of increasing delays, and (4) self-locomotion experience improves the use of social cues. Indeed, a study by Horobin and Acredolo (1986) showed that infant attentiveness toward the correct location in the A-not-B task was predictive of task performance, and self-locomotion experience was related to better task performance and higher attentiveness. To more fully unravel if, and if so, how, infant self-locomotion changes children’s interaction with the world around them, recent studies have used novel techniques to capture what infants are seeing as they are moving, showing that different modes of locomotion (crawling vs walking) allow children to interact with objects and people differently (eg, Clearfield, 2011; Karasik et al., 2011; Kretch et al., 2014). For a discussion of these techniques and related findings, see Box 9.1.

Whereas the finding that self-locomotion and spatial memory are linked in infancy is well established, much less research has been devoted to addressing this question in older children. There is some evidence to suggest that not so much self-locomotion, but exploration in infancy, is still linked to spatial memory later in childhood. Oudgenoeg-Paz, Leseman, and Volman (2014) studied infant self-locomotion milestone achievement and spatial exploration during the first 2 years of life in relation to spatial memory, as assessed with the Dot Matrix task at 4 and 6 years of age. Infant self-locomotion milestone achievement was related to spatial exploration, but not to spatial memory. However, spatial exploration in infancy was related to spatial memory in childhood. These findings, taken together with those from infant studies (Campos et al., 2000; Horobin & Acredolo, 1986; Kermoian & Campos, 1988; van den Brink & Janzen, 2013), suggest that the influence of self-locomotion on spatial memory may weaken as the time interval between achievement of self-locomotion milestones and the assessment of spatial memory skill increases. This may not be surprising given the fact that interindividual differences in self-locomotion milestone achievement are typically only a few months, while the time interval in the study by Oudgenoeg-Paz et al. was a few years. Yet, the extent to which children are engaged in spatial exploration in infancy, which adds up to a great number of hours over
time, does have a more stable relation with spatial memory later in childhood. Further studies are needed to unravel how motor development, exploration, and spatial memory are related beyond infancy.

This is also important for research on spatial cognition in clinical groups, such as ASD (Box 9.2), CP (Box 9.3) and NLD (Box 9.4).

**BOX 9.2 Spatial Cognition in ASD**

ASD is characterized by deficits in social communication and interaction, and restricted, repetitive patterns of behavior, interests, or activities (APA, 2013). However, as suggested by the term pervasive developmental disorder, ASD is more than the diagnostic criteria described above. It has been associated with delays, deficits, and strengths, across the whole range of developmental domains, including motor development, perception, play, language, and spatial cognition (Volkmar, Lord, Bailey, Schultz, & Klin, 2004; Yirmiya & Charman, 2010).

ASD has been associated with both strengths and weaknesses in spatial cognition (Edgin & Pennington, 2005; Müth, Hönekopp, & Falter, 2014). A meta-analysis, that included studies with both children and adults with ASD, demonstrated superior performance of children and adults with ASD compared to a typically developing group on the Embedded Figures Test (EFT) and Block Design Test (BDT; Müth et al., 2014). In the EFT, participants are presented with cards depicting images made up of lines with embedded geometrical shapes, such as triangles or rectangles. A target shape is presented, which the participant is asked to locate as quickly as possible in the image (Müth et al., 2014). In the BDT, participants are asked to use blocks to recreate a two-dimensional pattern that the participant is presented with on a card (Müth et al., 2014). While superiority for the ASD group was found, effect size was small and there was a large amount of heterogeneity (Müth et al., 2014).

Regarding spatial memory in ASD, results are also inconsistent. One study found that high-functioning adolescents with ASD made more errors than a matched group of typically developing controls on the CANTAB (Cambridge Neuropsychological Test Automated Battery) spatial working memory task, and were less likely to consistently use a specific organized search strategy to complete the task (Steele, Minshew, Lun, & Sweeney, 2007). The CANTAB task requires participants to find targets hidden in an array of boxes on a computer screen by using a touch screen to search the boxes. The task increases in difficulty from three to eight targets. To complete the task successfully, the participant must remember the spatial locations where the target has been

(Continued)
BOX 9.2 Spatial Cognition in ASD—cont’d

found previously, update this information as new targets are found, and inhibit incorrect responses (Edgin & Pennington, 2005). Other studies, using the same task, did not find differences between children with ASD and a matched control group in spatial working memory (Edgin & Pennington, 2005). Moreover, no differences were found when comparing 3- to 4-year-old children with ASD and a matched typically developing control group on the A-not-B task (Dawson et al., 2002; Yerys, Hepburn, Pennington, & Rogers, 2007), which also measures visuospatial working memory.

Also for another visuospatial ability, mental rotation, no clear differences in accuracy are found between the children and adults with ASD and typically developing controls (Falter, Plaisted, & Davis, 2008; Müth et al., 2014). However, with regard to response times in mental rotation, some studies report faster processing for individuals with ASD (Falter et al., 2008), while other studies demonstrate slower processing for the ASD group (Pearson, Marsh, Hamilton, & Ropar, 2014). These differences in results have been attributed to the type of processing strategy used. Two different strategies can be used for mental rotation. In a configural processing strategy a person will use the entire object and transform it through mental rotation (performing a holistic rotation), while in a feature-based strategy, a person will try to verify the identity and location of a key feature of an object and match it with a target (Pearson et al., 2014). When adults with ASD use a local feature-based processing strategy, they are faster than typically developing participants, and when they use a configural processing strategy, they are slower (Pearson et al., 2014). The type of processing strategy may be dependent on the familiarity of the stimuli with participants with ASD using a feature-based strategy with novel stimuli and a configural processing strategy with familiar stimuli (Behrmann et al., 2006; Müth et al., 2014).

With regard to spatial navigation, results regarding ASD are dependent upon the kind of navigation tested. Route-based navigation relies on gradually learned, inflexible, egocentric representations of specific sequences of landmarks, junctions, and so forth. This is the type of strategy that we typically rely on when following familiar routes. Routes are easily disrupted if a landmark or other information is removed. On the other hand, survey-based navigation relies on flexible, allocentric representations, or “cognitive maps” of the layout of the environment. This is the type of strategy that people use when familiar route following is not possible (Lind, Williams, Raber, Peel, & Bowler, 2013). Adolescents and adults with ASD show typical performance on tasks, which only require route-based navigation (Caron, Mottron, Rainville, & Chouinard, (Continued)
Spatial Cognition in ASD—cont’d

2004), but have impaired survey-based navigation skills (Lind et al., 2013). This may also explain why both children and adults with ASD insist on always taking familiar routes and feel stressed and anxious when they have to deviate from a familiar route (Lind et al., 2013).

Theories Explaining Spatial Cognition in ASD

Several theories attempt to explain spatial cognition in ASD, namely the Weak Central Coherence account (Happé & Frith, 2006), the Enhanced Perceptual Functioning theory (Mottron, Dawson, Soulières, Hubert & Burack, 2006), the Extreme Male Brain theory (Baron-Cohen, 2002), and the Executive Dysfunction Hypothesis (Ozonoff, Pennington, & Rogers, 1991).

Both the Weak Central Coherence account and Enhanced Perceptual Functioning theory assume that individuals with ASD have a bias toward local processing as opposed to the global processing tendency that typically developing individuals display (Happé & Frith, 2006; Mottron et al., 2006). Both of these theories predict superior performance for the EFT and the BDT, which is consistent with empirical findings (Mùth et al., 2014). The Extreme Male Brain theory assumes that individuals with ASD represent extreme cases of the normal male (brain) profile (Baron-Cohen, 2002). One prediction from this theory would be that the ASD group performs better on the mental rotation task, because studies have shown that males perform better than females (Falter et al., 2008). However, no superiority regarding accuracy was found for the ASD group (Falter et al., 2008; Mùth et al., 2014). Regarding spatial navigation, the Extreme Male Brain theory would also predict superior performance for individuals with ASD. Results however indicate that ASD are impaired in spatial navigation when survey-based navigation skills are needed (Lind et al., 2013) and that they perform typical with route-based navigation (Caron et al., 2004). The Executive Dysfunction theory assumes that individuals with ASD are impaired in executive functions, such as planning, working memory, flexibility, and inhibition (Hill, 2004; Ozonoff et al., 1991). This theory predicts impairments on a number of visuospatial abilities, but specifically on spatial working memory tasks. Empirical findings regarding spatial working memory in ASD are inconsistent, with some studies reporting impairments (Steele et al., 2007) and other studies demonstrating intact spatial working memory in ASD (Edgin & Pennington, 2005).
BOX 9.2 Spatial Cognition in ASD—cont’d

Spatial Cognition in ASD: An Embodied Dynamic Systems Perspective

Although these four theories provide interesting and plausible explanations for spatial cognition in ASD, none of these theories is able to explain all research results and corresponding inconsistencies. Moreover, a shortcoming of these theories is that they assume a rather static impairment without taking development and the role of developmental cascades across domains into account (López, 2015; Paterson, Brown, Gsödl, Johnson, & Karmiloff-Smith, 1999). As explained in this chapter, according to an embodied dynamic systems perspective, spatial cognition emerges from the interaction of a child and its environment, and the development of spatial cognition is influenced by other skills and processes, including motor skills, exploration, perceptual skills and social skills. Various studies have demonstrated that, in addition to the diagnostic criteria for ASD, such as social-communicative impairments, delays and deficits in fine, and gross motor skills are present in young children with ASD or at risk for ASD across all ages and levels of functioning (Bhat, Landa, & Galloway, 2011; Fournier, Hass, Naik, Lodha, & Cauraugh, 2010; Gernsbacher, Sauer, Geye, Schweigert, & Goldsmith, 2008; Landa & Garret-Mayer, 2006). Children with ASD are also different in their exploratory behavior. They display more rotating, spinning, and unusual visual exploration, and stereotyped, repetitive, and restricted uses of objects (Baranek, 1999; Bruckner & Yoder, 2007; Ozonoff et al., 2008; Wetherby et al., 2004; Williams, Costall, & Reddy, 1999), and spend less time in exploration (Koterba, Leezenbaum, & Iverson, 2012; Pierce & Courchesne, 2001) than children with developmental delays and typically developing children. Studies indicate that both motor skills and exploratory behavior are related to the development of visuospatial cognition in ASD (Hellendoorn et al., 2015), that joint engagement (shared attention) with an adult (experimenter and parents) is related to visuospatial abilities in children with ASD (Carpenter, Pennington, & Rogers, 2002), and that motor demands in a task influence the speed of information processing in ASD, that is, when a task demands a lot of motor output (action) this interferes with the ability to process information in children with ASD (Kenworthy, Yerys, Weinblatt, Abrams, & Wallace, 2013). These studies demonstrate that spatial skills are influenced by other skills and processes.

Spatial cognition in turn also influences other skills in ASD. Visuospatial information processing is, for instance, related to motor coordination deficits (Salowitz et al., 2013). Since ASD is best known for the deficits in social communication and interaction, it is also interesting to examine the relationship between spatial cognition skills and social skills. Some researchers suggest that spatial (Continued)
perspective taking is related to social skills since spatial perspective taking is necessary to perceive the affordances (the action possibilities) for others (Creem-Regehr, Gagnon, Geuss, & Stefanucci, 2013). In this way spatial perspective taking allows humans to make predictions about what another person is likely to do next. This ability to predict another’s behavior enables a person to adjust his or her own actions to the behavior of their interaction partner (Creem-Regehr et al., 2013). Studies also indicate that spatial cognition is related to gaze-following (Lind et al., 2013; Trafton & Harrison, 2011). Other researchers also believe that visual perspective taking, the ability to see the world (literally) from another person’s perspective, is related to the social skill of seeing another person’s perspective (Pearson, Ropar, & Hamilton, 2013). If this is the case then it is expected that children with ASD not only do display social difficulties, but are also impaired in visual perspective taking. Some studies indeed indicate that children with ASD have difficulties with visual perspective taking tasks (Pearson et al., 2013). In addition, studies demonstrate that a more detail-focused processing style (ie, faster disembedding on EFT and strength in BDT) is related to more social impairments (Jarrold, Butler, Cottington, & Jimenez, 2000; Pellicano, Maybery, Durkin, & Maley, 2006) and more impaired, autism-like play (Kuschner & Bennetto, 2007) in individuals with ASD.

In conclusion, results regarding spatial cognition in ASD are inconsistent. In order to understand the development of spatial cognition in ASD, it is necessary to take into account the fact that individuals with ASD interact in a different way with their physical and social environment and to consider interrelationships across developmental domains that are present in ASD. Taking this into account may also help to explain the large heterogeneity (the interindividual variability), the occurrence of developmental regression, the inconsistency in findings and the intraindividual variability that are reported in many studies for individuals with ASD (Dinstein et al., 2012; Mùth et al., 2014; Rogers, 2004). From a dynamic systems embodied cognition account, these phenomena can be explained as emerging from minor and major changes in the individual or the environment (and the interaction between them), and from the interrelationships between developmental domains that continuously interact with each other in individuals with ASD. These phenomena are hard to explain from the aforementioned theories that explain ASD since these theories assume a static cognitive impairment as explanation for ASD and for the differences between individuals with and without ASD in spatial cognition.
CP is the most common motor disability among children (Cans, 2000). CP is the general term for “a group of disorders of the development of movement and posture, causing activity limitations, which are attributed to non-progressive disturbances that occurred in the developing fetal or infant brain. The motor disorders of CP are often accompanied by disturbances of sensation, perception, cognition, communication, and behavior, by epilepsy, and by secondary musculoskeletal problems” (Rosenbaum et al., 2007, p. 9). CP can have multiple causes, which can occur in the prenatal or perinatal period, or postnatal during the first year of life. The heterogeneous nature of CP means that the population of children with CP is characterized by much variation.

According to the Surveillance of Cerebral Palsy in Europe (SCPE) guidelines (Cans, 2000), the subtypes of CP in terms of the motor disorder can be classified into three subtypes: spastic, dyskinetic, and ataxic CP. Mixed presentations also occur, in which case the dominant subtype of the presentation determines the classification. The spastic subtype of CP can be subclassified, based on anatomical distribution, into unilateral, when one side of the body is affected (often referred to as hemiplegia), and bilateral, when both sides of the body are affected (often referred to as diplegia when the legs are most affected). The most common subtype of CP is spastic CP, as around 80% of the persons with CP are classified in the spastic subtype.

CP and Spatial Cognition: Evolution of Studies From “Near” to “Further” Space

It is generally agreed upon that limitations in movement might contribute to limitations in spatial cognition among children with CP. In fact, this idea is not new. An exemplary review by Abercrombie (1964) at a time when research interest in studying consequences of CP was thriving, showed a large number of difficulties including shape copying and assembling simple jigsaw puzzles. For many years, research remained focused on unraveling and explaining performance on manual tasks challenging children with CP to move their hands and arms through a rather restricted part of space, that is, close to the child’s body. A recent example of such a study showed (again) that visual navigation in this “near” space is compromised in children with CP. Adolescents (aged between 13 and 16 years; verbal IQ within the normal range) born premature (27–33 weeks of gestation) with periventricular leukomalacia, of whom 8 out of 11 were classified as bilateral spastic CP, performed more poorly on a paper-and-pencil labyrinth test compared to premature-born adolescents without brain lesions and term-born adolescents (Pavlova, Sokolov, & Krageloh-Mann, 2007). In line with
other studies, navigation ability on this task in “near” space was specifically linked to (frontal) lesions in the right hemisphere.

It is only by the end of the 1980s, more than 20 years on from Abercrombie’s review, that studies emerged investigating the ability of children with CP to make judgments and perform actual movements in “further” space, shifting the focus more toward the role of locomotion in spatial cognition abilities. Children were asked to judge from a distance whether they were able to move through apertures (eg, curtains which could be drawn), including sometimes locomotion conditions in which children actively navigated through space (eg, Howard & Henderson, 1989; Savelsbergh, Douwes Dekker, Vermeer, & Hopkins, 1998). As such, space literally opened up for other paradigms to be studied. It was shown that typically developing children (matched for age and intellectual ability to the children with CP) outperformed the children with CP when judging the size of an aperture in relation to their own body dimensions. In addition, children suffering from dyskinetic CP performed better than children with the spastic subtype of CP in judging whether they would be able to move through apertures of varying widths and heights (Howard & Henderson, 1989). The most plausible explanation (at that time when MRI scans were not yet routinely performed) being the underlying type of brain damage suffered by children with spastic CP more likely to encompass areas that serve perceptual functions.

On a similar task, except for the addition of a condition in which children actually had to move through the aperture, it was found that when performances in passing through apertures (measured at two occasions 12 months apart in two age groups: 5–8 years old and 9–13 years old) were adjusted for differences in body width, children with CP who could stand and walk unaided (CP-Walk), children with CP who were confined to a wheelchair (CP-Wheel), and nondisabled children, irrespective of age, had similar outcomes: all children were able to match their body width with the aperture width when locomoting toward and through the apertures (Savelsbergh, Douwes Dekker, Vermeer & Hopkins, 1998). There was one exception, namely the younger group of ambulant children with CP (CP-Walk; 5–8 years old): they made the largest overestimations of aperture width relative to body width while judging the aperture from a distance, but did not differ from the other groups in using body-scaled information to actually pass through the opening. The authors suggested that control of locomotion (ie, a standing position with more variability in sway vs a relatively more stable body position while sitting in a wheelchair) might be one plausible explanation for this finding. Likewise, the (Continued)
BOX 9.3 Navigating “Near” and “Further” Space in Children With Cerebral Palsy—cont’d

improved accuracy in older children may suggest an influence of extended experience.

Navigating Streets and (Magic) Carpets

Imagine the following: a busy street, cars parked on both sides, no pedestrian crossing nearby. This is a familiar scene for many children walking to, or on their way home from, school. A quite challenging task, because it requires the child to position himself in such a way as to oversee the situation given the stationary obstacles (parked cars), to accurately estimate the time of arrival of moving obstacles (oncoming traffic) and at the same time relate this information to his own body speed both in the initial phase while standing still on the pavement and during the actual dynamic crossing moments. This is a demanding situation for any child, but what if a child with CP who is independently mobile wants to cross the street (te Velde, Savelbergh, Barela, & van der Kamp, 2003)? Are children with unilateral spastic CP (excluding those with moderate to severe intellectual disability) just as accurate as their nondisabled peers in judging whether it is safe enough to cross? Given a simplified laboratory setting (low-speed traffic, a bicycle, approaching from one direction) and compared at a group level ($n = 10$ in each group; age range 4–14 years) they were just as accurate, irrespective of whether they started from a standing condition or a locomoting position (ie, already in motion on the pavement). However, within-group differences among children with unilateral spastic CP showed greater variability than among nondisabled peers. Children with right hemisphere lesions were more inconsistent (ie, they sometimes crossed the street while there was no sufficient time to do so safely or lingered on the pavement when they could have safely crossed) in their behavior compared to children with left hemisphere lesions. In order to explain this, the authors refer to the presumed egocentric (position of objects relative to the observer) processing of visual information of the right hemisphere (Postma, Sterken, de Vries, & de Haan, 2000) and the assumption that spatial information processed through the right hemisphere is used to guide movements (Kosslyn, 1991). While in need of replication given the small sample size, extending the design to a more real-life situation (ie, high-speed traffic approaching from two directions) and to a more diverse group of children with CP, the authors argued that these results highlight the need for discriminating between different subtypes of CP when studying spatiotemporal tasks (te Velde et al., 2003). In other words, brain damage in itself does not explain all the variance in individual differences between children in their ability to navigate through space, an assumption which can sometimes still be (implicitly) detected in the literature.

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Moving on from streets to carpets. Starting from the point that “near” space (ie, space in which children can reach such as the manual tasks described before) and “further” space (ie, navigational space in which to walk/wheel around) involve different cognitive strategies and brain networks, children with spastic CP independently walking without aids (5–12 years of age) were compared to a sample of typically developing children matched and unmatched for age and sex on two tasks (Belmonti, Fiori, Guzzetta, Cioni, & Berthoz, 2015). The first task was the classic Corsi Block-tapping Task (CBT). The second task was an adapted version of the CBT, called the Magic Carpet, in which the children were required to walk (ie, using real body motion) on tiles laid out on the floor using the same short-term memory assessment procedure as with the CBT (ie, reproducing a sequence of blocks as pointed out by an experimenter, or walking over the tiles that light up one after the other automatically). It appeared that spatial memory in children with CP was more impaired on the “near” (ie, reaching) space than the “further” (ie, navigational) space task. Three explanations were provided: (1) more complex tasks (ie, the Magic Carpet) involve more factors, but also more possible mechanisms for compensation; (2) egocentric reference frames that are mainly used in reaching space are particularly impaired in children with CP; and (3) (simply) the larger stimuli used in the Magic Carpet are better perceived and stored by children with visual deficits. As in other studies (eg, Pavlova et al., 2007) performance on both the CBT and Magic Carpet were related to global right hemisphere impairment indicating a general association with spatial functions. In conclusion, many children continue to suffer from CP. Therefore, the question of what the possible consequences for navigating space are of motor disabilities that delay the acquisition of independent locomotion or impair the quality of locomotion once it is acquired remains topical (Anderson et al., 2013). Unfortunately (but not surprisingly), no definite answer(s) can be given since this is a complex field of investigation which few studies have yet embarked upon. Moreover, as Anderson and colleagues argue, the major problem is separating the role of brain damage from that of mobility impairment when studying deficits in children with CP. As brain damage is often the cause of the primary motor impairments, that same damage is evidently implicated in any cooccurring spatial-cognitive deficits. Having said that, most studies among children with CP “suffer” from the fact that the level of explanation for deficits (still) mainly focuses on the presence, extent and type of brain lesions despite growing evidence that experience in locomotion and exploration does matter when examining individual children’s performances. Nevertheless, quality and experience of locomotion and exploration experience are until now (Continued)
BOX 9.3 Navigating “Near” and “Further” Space in Children With Cerebral Palsy—cont’d
largely ignored, which potentially might harm the rise of new intervention strategies. As such, maybe the time has come to introduce new paradigms and tests for studying and, eventually, remediating spatial deficits in children with CP (Berthoz & Zaoui, 2015), such as the “locomotor trajectory” paradigm in which the shift from “near” to “further” space is seen as necessary in order to effectively deal with, and make use of, the demands of the environment.

BOX 9.4 Nonverbal Learning Disability
Nonverbal learning disability (NLD) is the term used to describe people who have normal or even high verbal skills but show weak skills in nonverbal domains, especially in the visuospatial domain. This disability has been of interest to researchers and clinicians since it was described in 1967 by Johnson and Mykelbust and later extensively studied by Rourke (for a review see Mammarella & Cornoldi, 2014; Spreen, 2011). Despite extensive research, the diagnostic criteria of NLD as well as its prevalence are still unclear. Moreover, the symptoms of NLD often resemble that of other disabilities such as Asperger’s syndrome (Semrud-Clikeman, Goldenring Fine, & Bledsoe, 2014; Spreen, 2011). Mammarella and Cornoldi (2014) analyzed 35 studies on children with NLD and concluded that the factor that distinguishes children with NLD most from typically developing children (ie, effect sizes reported are the largest) is visuospatial intelligence. Other factors are: discrepancy between verbal and nonverbal intelligence, poor visuoconstructive and fine-motor skills, discrepancy between reading achievement and mathematical achievement. In the last group with smaller effect sizes, but still significant differences they list visuospatial memory and socioemotional skills. Based on this analysis, Mammarella and Cornoldi suggested five criteria for diagnosing NLD. The first criterion has to be met and at least two out of criteria 2—4 also have to be met. The fifth criterion is possibly an associated criterion. The five criteria are:
1. Poor visuospatial intelligence with a relatively good verbal intelligence;
2. Visuoconstructive and fine-motor impairments;
3. Poor mathematical achievement at school with relatively good reading decoding skills;
4. Spatial working memory deficits;
5. Emotional and social difficulties.

(Continued)
BOX 9.4 Nonverbal Learning Disability—cont’d

While only one of these criteria concerns academic achievement, this disability can have profound effects on the performance of children in school, as performance in many subjects requires visuospatial and fine-motor skills (Cornoldi, Venneri, Marconato, Molin, & Montinari, 2003).

NLD and Spatial Cognition

Poor spatial skills are one of the main diagnostic criteria for NLD. Multiple studies reveal difficulties for these children in spatial memory. For example, Mammarella, Lucangeli, and Cornoldi (2010) presented 7–11 years old typically developing children and children with symptoms of NLD with a series of tests designed to measure spatial memory, visual memory, and arithmetic skills. The spatial memory tasks involved recalling the location of dots presented in a matrix, lines presented in a matrix, and light bulbs presented in a circle. The stimuli were presented either sequentially (ie, one dot, line or light bulb at a time) or simultaneously (ie, all dots, lines or light bulbs at once). The number of stimuli varied from two to eight. After the presentation, the children saw the stimuli again and had to judge if the locations were the same as what they had seen before. In the visual tasks children saw a series of two to eight nonsense shapes, fish or balloons in different patterns of filling. After the initial presentation of the visual stimuli, children again were presented with the stimuli and asked to judge if the shapes, fish, or balloons were the same as the ones previously presented. Results revealed that children with NLD symptoms performed worse than typically developing children on the spatial tasks but not on the visual tasks. The NLD children, interestingly, were not different on the sequential spatial task involving the lines. Mammarella et al. suggested that this might be because the children focused on the shapes created by the lines rather than on the locations, thus making this more a visual than spatial task. This study suggests that the difficulties experienced by children with NLD are highly specific to the spatial domain. In addition, the children with NLD showed poorer performance on arithmetic tasks involving a spatial component, such as carrying and aligning numbers in columns. This suggests that the difficulty with arithmetic might also be essentially a spatial difficulty.

In another study, Narimoto, Matsuura, Takezawa, Mitsuhashi, and Hiratani (2013) showed 8–11 years old children with NLD, children with verbal comprehension difficulties and typically developing children a stimuli consisting of 3, 5, or 7 green squares at random locations. Following this, a second frame with the same squares was shown and children had to judge if one of the squares (indicated by a red outline) had shifted its location. The task had two conditions, one with a minimal change in location of the target and one with a larger change (maximal change). Results showed that children with NLD performed worse than typically developing children and children with verbal comprehension difficulties.

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9.6 GENERAL DISCUSSION

In the current chapter, we have aimed to provide a review of the literature on the development of spatial cognition in young children from a dynamic systems embodied cognition perspective, in particular focusing on studies that have investigated the link between motor development, exploration, mental rotation, and spatial memory (including memory for object locations, orientation, and navigation). From the dynamic systems embodied cognition theory, the prediction is that motor development, exploration, and advances in spatial cognition are strongly intertwined. In general, the studies reviewed in this chapter provide support for this hypothesis: there is evidence that infant self-locomotion is related to advances in spatial

**BOX 9.4 Nonverbal Learning Disability—cont'd**

on the task in the condition with the minimal change in location, but not on the maximal location change. All children performed worse on the maximal change task than on the minimal change task. The authors argued that in order to succeed on the minimal change task, the relation between the individual squares have to be coded rather than their absolute location. This suggests that spatial memory deficits of children with NLD are at least partially related to a difficulty with processing spatial relations between objects.

**NLD From an Embodied Cognition Approach**

From an embodied cognition perspective, it is interesting that the pattern of difficulties characterizing children with NLD involves fine-motor difficulties. It is possible that due to these motor difficulties, these children explore their environment in a less optimal manner. If they are less able to successfully engage in activities including the manipulation of spatial relations such as building with blocks, stacking cups and doing puzzles, then they have less experience with exploring spatial relations in their environment. This reduced experience, in turn, might mean that their knowledge of spatial concepts is not as well-grounded in sensorimotor real-life experiences as it would be if they had gained more experience with manipulating spatial relations. Studies with typically developing children reviewed in this chapter (eg, Oudgenoeg-Paz et al., 2015) suggest that exploration of spatial relations is an important predictor of future spatial skills, including spatial memory. Therefore, reduced exploration (caused by poor fine-motor skills) seems to be one possible mechanism underlying the development of NLD. However, this is merely a hypothesis which will have to be put to an empirical test in future studies.
memory and mental rotation, motor processes play a role in mental rotation from infancy through to adulthood, and infant exploration is related to spatial memory even at school age. Yet, the evidence is not as clear as it may seem upon first glance and there are several lines of investigation that need further study.

First of all, a current debate concerns how the role of motor processes in (spatial) cognitive function changes over developmental time (see Needham & Libertus, 2011). Whereas Thelen (2000) argued for an embodied view of cognition throughout the life span, others have suggested that the close ties between our body and actions on the one hand and cognition on the other becomes weaker over developmental time, as we leave the acquisition of some of the largest motor milestones (ie, sitting, crawling, walking) far behind us. To address this issue, Frick, Daum, Walser, and Mast (2009) investigated the role of motor processing in mental rotation in different age groups: 5-, 8-, and 11-year-olds, and adults. Study subjects at each age were given a similar experiment as Wexler and colleagues (1998) used (see section 9.3.1), in which they were asked to perform a manual and mental rotation task at the same time. Frick et al. (2009) found that when the direction of motor action was incompatible with the direction of mental rotation, this negatively influenced performance on the mental rotation task in 5- and 8-year-olds, but not in 11-year-olds and adults. Thus, they conclude that with development, cognitive processing may become increasingly distanced from motor processing. These findings seem to conflict with those of Wexler and colleagues (1998) and Moreau and colleagues (2011) who showed that motor processes and motor skill training were related to mental rotation performance in adults, respectively. Clearly, the changing role of embodiment in cognitive processing over developmental time requires further investigation, but this is no easy enterprise. Comparison across child and adult data is hampered by a number of factors. First, other developmental factors than the one under study may explain age-related differences (such as advances in inhibitory control, which Frick et al. (2009) suggest may contribute to explaining their age-related differences). Second, motor development is on at full speed in infancy; there is no later time when we learn such drastically new ways of moving about. As adults, we do learn new motor skills occasionally, such as ice skating or driving a car, but none of these skills offer such a thoroughly new perspective on the world as infants’ first successes in self-locomotion, neither are they typically trained as extensively. As such, a fair comparison of the role of motor processes and experience
in spatial cognition between adults and young children is challenging to make, to say the least. However, current evidence shows that even as adults our mental representations and cognitive functions are related to our physical body and actions, suggesting cognition remains embodied as we grow older (see, eg, Price & Harmon-Jones, 2010; Richardson, Spivey, Barsalou, & McRae, 2003).

Final, although the studies described in this chapter seem to fit in with a dynamic systems embodied cognition account of the development of spatial cognition, the evidence is not always conclusive. For example, as described in the section on mental rotation, mental rotation ability was related to the gross motor milestones standing and walking with assistance, but not to crawling in the study by Frick and Möhring (2013). In contrast, Schwarzer and colleagues (2013) reported a positive relation between crawling experience and mental rotation ability in infants of about the same age. Likewise, Campos and colleagues (2000) also describe a number of studies that fail to find support for the relation between self-locomotion and spatial memory in their review. Such discrepancies need not be ignored, and in fact may help further fine-tune the theory about the mechanism through which the development of spatial cognition occurs. In fact, given that each new mode of self-locomotion drastically alters infants’ interactions with the world (see Box 9.1), their opportunities for exploration, and the affordances they can discover, the impact of these different modes of self-locomotion on spatial cognition is likely to be at least partly unique. To further put the theory to the test, it seems important to start specifying hypotheses much more precisely—rather than testing the association between a range of motor milestones and spatial cognition, more specific hypotheses could be drawn up based on what is now known about the different ways the attainment of sitting, crawling, and walking influence infants’ visual perceptual experience (Kretch et al., 2014). In addition, it is worth considering whether infant self-locomotion may be unrelated to particular aspects of cognitive function—if such relations indeed prove to be absent, a “general” underlying developmental factor driving both self-locomotion and spatial cognition becomes a less likely explanation of study results (see also Oudgenoeg-Paz, 2014).

In relation to the latter point, the large majority of studies that report associations between motor development and spatial cognition are correlational in nature (but see Kermoian & Campos, 1988), thus not allowing
conclusions about the direction of effects. In particular, infants who acquire the ability for independent locomotion earlier may interact differently with the world around them before the onset of self-locomotion already. Several studies indeed point to such an effect, calling in particular for a role for motivation in learning new actions (von Hofsten, 2004, 2007). For example, Atun-Einy, Berger, and Scher (2013) investigated infants’ motivation to move, by assessing infants’ persistence to move relative to difficulty, the frequency of position changes, the proportion of time infants spent in motion, the extent to which external simulation was needed to elicit movement, and the infants’ preference for high or low energy activities. Infants were assessed each 3 weeks over the course of 5 months, from 7 to 12 months of age. Gross motor milestone achievement was also recorded (sitting, pulling-to-stand, crawling, and cruising). Infants with higher motivation to move at the first session were more likely to reach these milestones earlier than infants with lower motivation to move. In addition, there was evidence for a developmental cascade effect: motivation to move in each session was related to motor skill acquisition in the next session, and the opposite effect was also true. Similarly, Karasik, Tamis-LeMonda, and Adolph (2011) observed that the frequency at which crawling infants at age 11 months engaged with objects which were out of direct reach so that they had to locomote toward them, carried objects, and shared objects with their mother by moving toward her, predicted walking attainment at age 13 months. Thus, it appears that indeed, there is something different about the actions undertaken and the motivation for action in infants who achieve self-locomotion milestones earlier. In sum, through advancing motor development, infants acquire increasingly new means to explore their environment, which ultimately leads to increased understanding about the world. However, although much research has focused on the impact of motor development on exploration and spatial cognition, rather than the other way around, this is not to suggest that these relations are unidirectional. Rather, all aspects of the developing child and its environment can be seen as a clockwork with interlocking components that continuously interact.

A further aspect to consider in the development of spatial cognition is the social context in which behavior occurs. Whereas this chapter has focused on the affordances the physical world has to offer, the role of the social environment in cognition and action cannot be ignored (eg,
Tamis-Lemonda et al., 2008; Topál, Gergely, Miklósi, Erdőheyi, & Csibra, 2008). For example, Topál and colleagues (2008) have shown that infants’ performance on the A-not-B task depends partly on the infant picking up social-communicative information from the assessor who hides the toy. In this experimental study, infants perseverated much more often to the A location when the assessor engaged with them in a natural way during each hiding event, than when no such social information was available (ie, the assessor looked away from the infant or was not visible at all). These findings suggest that infants interpret what the assessor is doing as a general principle they are trying to convey (“look, toys like these are hidden here at A!”) rather than the idea that an object can be hidden in different locations at different time points. Thus, this study points to the crucial role of the social environment in performance on spatial cognition tasks; yet, few other studies to date have investigated the way children use social information in the area of spatial cognition, for example, when navigating.

To conclude, the studies reviewed in this chapter have shown that young infants already have rudimentary memory for object locations, and are able to orient themselves in the environment after having been moved about. Yet, these abilities further develop over the many childhood years to follow. In the current chapter, we have provided a review of the development of spatial cognition from an embodied dynamic systems view, in which cognitive “representations,” such as those required for mental rotation, are embodied and construed from the child’s active exploration of and interaction with the environment. Motor development is an important driving force in the opportunities children have for exploration (Gibson, 1988), yet the studies on children with physical handicaps show that motor development is not a necessary prerequisite for advances in spatial cognitive development (see Box 9.3; see also Campos et al., 2000). Mental processes, such as mental map formations used for navigation, may not become increasingly distant from the physical world over time; the crux to development and skill acquisition may rather lie in the increased flexibility with which we can use and integrate different sources of information to attain our goals (Nardini et al., 2006; Thelen, 2000; Von Hofsten, 2004), whether they are to fit a complex shape into an aperture, finding our way in the world, or remembering an objects’ location.
REFERENCES


Development of Spatial Cognition


