A PERCEPTION-ACTION APPROACH TO THE EARLY DEVELOPMENT OF SPATIAL COGNITION: THE IMPORTANCE OF ACTIVE EXPLORATION

Ora Oudgenoeg-Paz, Hanna Mulder

Presses Universitaires de France | « Enfance »

2021/1 N° 1 | pages 37 à 50

ISSN 0013-7545
ISBN 9782130828877

A perception-action approach to the early development of spatial cognition: The importance of active exploration

Ora Oudgenoeg-Paz and Hanna Mulder[a]

ABSTRACT

The ecological approach to child development stresses exploration of the environment as a central mechanism that drives development of spatial cognition. Through active exploration of affordances, which are possibilities for action defined by the child's (motor, cognitive and other) skills and the environment, children are thought to develop spatial skills over time. In the current paper, we review the state of the evidence for this theoretical mechanism with respect to the early development of spatial memory, spatial orientation, spatial process and spatial language in typically developing young children. We conclude that the knowledge base to date supports the notion that active exploration plays a key and specific role in spatial cognition. The evidence supports the idea that spatial cognition is grounded in daily physical interactions between children and their environment. We further discuss open questions and point directions for future research.

KEYWORDS: SPATIAL COGNITION, ECOLOGICAL PSYCHOLOGY, PERCEPTION-ACTION, EXPLORATION, MOTOR DEVELOPMENT.

RÉSUMÉ

Une approche perception-action du début de la cognition spatiale : l'importance d'une exploration active

L'approche écologique du développement de l'enfant voit l'exploration-del'environnement comme le mécanismecentral du développement de lacognition spatiale. Les enfants développeraient leurs compétences spatiales grâce à l'exploration active des possibilités d'action définies parleurscompétences(motrice,cognitiveetautre)et les opportunités offertes par l'environnement. Dans cet article,nous examinons cette hypothèse sur la base du développement précoce de la mémoire spatiale, de l'orientationspatiale, du traitement spatialet du langagespatial des jeunes enfants. Notre conclusion est que les connaissances actuelles soutiennent

[a] Department of Education & Pedagogy, Faculty of Social and Behavioural Sciences, Utrecht University, P. O. Box 80140 3508, TC Utrecht, Netherlands. *E-mails*: o.oudgenoeg@uu.nl ; h.mulder2@uu.nl

l'hypothèse d'un rôle clé et spécifique de l'exploration dans la cognition spatiale. Les données appuient l'idée que la cognition spatiale est fondée sur les interactions physiques quotidiennes entre les enfants et leur environnement. Pour finir, nous élargissons le débat à de nouvelles questions et pointons de possibles orientations futures de la recherche.

MOTS-CLÉS : COGNITION SPATIALE, PSYCHOLOGIE ÉCOLOGIQUE, PERCEPTION-ACTION, EXPLORATION, DÉVELOPPEMENT MOTEUR.

In the early years of life, spatial cognition shows a rapid and significant development (see for example: Mulder *et al.*, 2017; Pelphrey *et al.*, 2004; Schwarzer *et al.*, 2013). Spatial skills such as memory for location, spatial orientation and spatial language, are important for everyday functioning, and for academic attainment in science, technology, engineering and mathematics (STEM) and language as well as for complex social skills (Creem-Regehr *et al.*, 2013; Landau & Hoffman, 2005; Newcombe *et al.*, 2013). Therefore, it is important to understand what factors contribute to the early development of spatial skills.

In the current review we consider these factors from the prism of ecological psychology. This view was proposed by James Gibson and further elaborated on by Eleanor Gibson, Ulric Neisser and many others and stresses the central role of recurrent perception-action processes in development. Children both perceive information from the environment and also act on the environment, thus generating new information to be perceived (J. J. Gibson, 1979; E. J. Gibson & Pick, 2000; Thelen & Smith, 1996). These continuous perception-action cycles form the basis for the development of advanced cognitive skills as they enable children to learn about their environment (Adolph, 2019; E. J. Gibson & Pick, 2000; Thelen & Smith, 1996; Smith *et al.*, 1999; Smith & Gasser, 2005).

Affordances are a key concept within this theoretical framework. Affordances are the possibilities for actions that children have in their environment and are specified by the properties of the environment relative to the properties of the child (J. J. Gibson, 1979). In the course of development children engage in active exploration of their environment, which enables them to discover affordances and develop the skills to recognize them and act upon them. Discovering affordances entails that children learn to perceive their physical and social world and act on it. For example, children learn about where things are, if and how they can get there, what they can do with objects and how to communicate with social partners. Thus, learning about affordances through exploration is a crucial process in child development (Adolph *et al.*, 2000; E. J. Gibson, 1988; Smith & Gasser, 2005). Notably, children's opportunities for exploration change with developmental changes in perception and action skills. Importantly, when children acquire new motor skills (e.g., sitting, standing, walking) they also acquire new perception and action possibilities (Soska & Adolph, 2014; Gibson, 1988). Therefore, in line with the ecological approach, the current review focuses on the role of active exploration in the development of spatial cognition.

We focus mainly on two types of exploration that are most prominent in the literature. First, manual exploration of objects concerns children's exploration of the spatial-relational object properties. In this type of exploration children, for example, turn objects around to see them from different angles and combine objects by stacking them (e.g., Möhring & Frick, 2013; Oudgenoeg-Paz *et al.* 2014). Second, exploration through self-locomotion concerns children's exploration of the space around them by moving around independently (e.g., Kermoian & Campos, 1988; Oudgenoeg-Paz *et al.*, 2015). In the following sections, we first review evidence for the role of exploration in the development of spatial memory, spatial orientation (including navigation), spatial processing (including mental rotation) and spatial language. Second, we discuss the implications of this evidence and highlight open questions and directions for future research.

Spatial Memory

Children's skill in remembering the location of objects is one of the most extensively studied aspects of spatial cognition. Various studies have focused on the relation between spatial memory and motor development and exploration. Campos and colleagues (2000) reviewed multiple studies conducted in the 80's and 90's showing a consistent link between engagement in self-produced locomotion (i.e., crawling or walking) and success on spatial search tasks. Kermoian and Campos (1988) specifically showed that the experience that children gained with self-locomotion by using a baby walker (which can be seen as artificially gained experience) performed spatial search tasks better than children without self-locomotion experience. This suggests that the relation between self-locomotion and spatial memory is causal rather than due to general maturation factors.

A few recent studies have shown that exploration relates to spatial memory, and suggest that exploration may be a mediator in the association between self-locomotion and spatial memory. First, a longitudinal study showed that children who were engaged in more exploration of spatial relations (i.e., through stacking, inserting etc.) at age two years had better spatial memory skills at ages four and six years. Interestingly, earlier age of walking attainment predicted exploration at age two but not spatial memory at ages four and six, suggesting that while learning to walk might be important in the short-term, in the long-term it is exploration, which is initially facilitated by walking, that predicts spatial skills (Oudgenoeg-Paz *et al.*, 2014). Similarly, in a different study, exploration involving self-locomotion (crawling and/or walking) at age 20 months, was not related to spatial memory at age two years. However, in the same dataset, exploration of spatial properties of objects (e.g., via making combinations) at age 20 months was found to predict better spatial memory skills at age 24 months (Oudgenoeg-Paz *et al.*, 2015). Finally, Muentener *et al.* (2018) measured what they defined as the efficiency of exploration during four time points over a nine-month period. The efficiency of exploration was defined as the number of different ways children discover to use a toy while exploring. Thus, this measure can be seen as a measure of the breadth of exploration. Infants were aged between five to 19 months at the start of the study. Individual differences in the efficiency or breadth of exploration were found to be relatively stable and positively predicted visuospatial working memory at age three years, as measured with the Wechsler Scales of Preschool and Primary Intelligence (WPPSI; Wechsler, 2002). Thus, there is consistent evidence that exploration and spatial memory are positively related in the infant and toddler years.

Several explanations have been suggested for the reason why exploration through self-locomotion is associated with spatial memory. Campos and colleagues (2000) note that experience with exploration through self-locomotion might enable infants to improve their attentional discrimination between relevant and irrelevant stimuli, improve goal-directed behavior, and improve the use of social cues. Earlier work supports the idea that better attention is related to better spatial memory performance, and experience with self-locomotion is related to both attention and spatial memory (Horobin & Arcedolo, 1986). Recent work further supports this by showing that walking experience is related to performance on a selective attention task (Mulder *et al.*, under review).

To summarize, multiple studies show that exploration with objects and exploration through self-locomotion facilitates advances in spatial memory. Explaining mechanisms are hypothesized to be advances in selective attention facilitated by self-locomotion and changes in the way infants interact with objects and people. Thus, changes in action possibilities generate new perceptual information and these new perception-action cycles propel advances in spatial memory.

Spatial Orientation

Though less extensively studied compared to spatial memory, empirical evidence also attests to the link between spatial orientation and navigating skills and exploration. In an early study by Acredolo and colleagues (1984) 12-month-old infants were asked to retrieve a toy they saw hidden in one of two identical wells. To retrieve the toy infants had to move around the display. Children who were allowed to locomote by themselves performed much better than infants who were carried by caregivers. This effect was due to visually tracking the correct location while locomoting. Similarly, van den Brink and Janzen (2013) have shown that toddlers who have more opportunities for spatial exploration in their daily lives performed better on a task requiring them to maintain their spatial orientation while their perspective changes. In this study, children aged between 30 and 36 months saw a bird disappearing behind one of two trees in a virtual reality scene. Then, the camera changed perspective by 90 degrees and children, who were sitting the whole time, had to find the bird. Children who were more independent in their daily functioning and therefore had more opportunities for spatial exploration performed this task better.

Multiple studies have further stressed the advantages of active locomotion versus passive locomotion for performance on tasks requiring spatial orientation and navigation in toddlers and children aged up to six years. In these studies, children who were allowed to explore a space using active locomotion (e.g., by walking around or moving their own wheelchair) performed better on spatial orientation or navigation tasks in this space, compared to children who explored the space using passive locomotion (e.g., were carried or pushed in their wheelchair; Feldman & Acredolo, 1979; Hazen, 1982; Foreman *et al.*, 1990). Finally, a study by Clearfield (2004) demonstrates the importance of perception-action processes in learning to successfully navigate. In this study, infants (12 and 14 months old) were asked to find their mother in an octagonal arena with several landmarks. Results showed that experienced crawlers and experienced walkers performed better than novice crawlers and walkers. Although novice walkers were experienced crawlers, they performed worse than experienced crawlers. These findings suggest that children's performance are then a 'soft assembly' of the perceptual information available to them and their action possibilities. Thus, as children start to walk, this brings about changes in perception and action leading to a change in affordances. The process in which children adjust to these new affordances requires attentional resources and therefore leads to a temporary setback in performance. In sum, evidence shows that exploration involving self-locomotion through the environment propels spatial orientation and navigation skills possibly because of better visual attention during active self-locomotion (as opposed to passive locomotion). These studies do not show a specific advantage to walking over crawling, but they do show that the experience gained with crawling does not transfer to children's skills once they start walking (see also Adolph, 1997).

Spatial Processing (Mental Rotation)

In recent years, spatial processing and specifically mental rotation has also been widely studied from a perception action perspective. A study using a violation of expectation paradigm showed effects of manual exploration on mental rotation skills. In this study, infants were shown a symmetrical object on a screen with different colours used for the back and front of the object that was then rotated out of sight. When the object was shown again, it was either the same object but rotated (congruent condition) or a rotated mirror image of the object (incongruent condition). If infants look longer in the incongruent condition this is taken to indicate preference for novelty and therefore understanding that this image is impossible. In order to understand this, infants need to be able to mentally rotate the originally introduced image. The study showed that six-months-old infants who first manually explored the object presented on the screen performed this task better than infants who did not have this experience (Möhring & Frick, 2013). In a follow-up study, the authors found that similar to six-month-old infants also eight-month-old infants did not look longer at the incongruent condition when they received only observational experience. However, ten-months-old infants did succeed on this mental rotation task with only observational experience. In the group of ten-month-olds, attainment of several motor skills (i.e., tilting a glass, pulling to stand, standing and walking with assistance) predicted success on this task. The strongest prediction was found for walking with assistance (note that here we refer to the motor milestone rather than using a baby walker). This suggests that even very early experience with changes in perspective and action possibilities enables infants to achieve more advanced reasoning about spatial relations, that might become more independent from their own location and perspective (Frick & Möhring, 2013).

Further support for this idea comes from a study using the same paradigm without the exploration phase, showing that nine-month-old crawling infants performed the task better than same-aged infants that could not yet crawl (Schwarzer *et al.*, 2013). A longitudinal study further showed that children who engaged more in exploration through self-locomotion at age 20 months showed better spatial processing skills (as measured by the block design task from the WPPSI) at age 32 months (Oudgenoeg-Paz *et al.*, 2015). This task requires children to replicate patterns of increasing difficulty of two coloured blocks. This task requires advanced spatial processing skills, including mental rotation (Wechsler, 2002). Exploration through self-locomotion also fully mediated the positive effect of early walking attainment on block design performance. However, the same study also found that spatial-relational object exploration at age 20 months did not predict spatial processing at age two years (Oudgenoeg-Paz *et al.*, 2015).

This last finding might seem to contradict the findings described above by Möhring and Frick (2013) and Frick and Möhring (2013). However, note that also in the study by Frick and Möhring (2013) the effect of object exploration was no longer seen as children grew older. The children in the study by Oudgenoeg-Paz *et al.*, (2015) were even older than the children in this study. Thus, we can conclude that the skills of spatial processing and specifically mental rotation appear to be facilitated by both (certain types of) object exploration and exploration through self-locomotion. However, evidence to date seems to suggest that perhaps, at first, children seem to benefit from specific manual exploration of objects. Following this, later on in infancy and in the toddler years, experience with changing perception and action possibilities, seen with the attainment of motor milestones and especially self-locomotion appears to enable children to generalize their spatial processing skills. Clearly more work is still needed to test these hypotheses.

Spatial Language

Finally, though less extensively studied, the domain of spatial language poses an interesting additional domain. In recent years, multiple studies have shown that motor development is related to advances in general language development (e.g., Libertus & Violi, 2016; Oudgenoeg-Paz *et al.*, 2012; Walle & Campos, 2014). However, as exploration through self-locomotion and exploration of spatial-relational object properties is specifically linked to obtaining spatial skills (see sections above), it can be expected that these types of exploration would also be related to spatial language development. The longitudinal study by Oudgenoeg-Paz *et al.* (2015) indeed provides support for this idea. In this study child knowledge of locative prepositions and of movement verbs containing a direction (such as push or pull) was measured at age 36 months. Results show that earlier attainment of walking predicts better knowledge of spatial language at 36 months, and that effect is partially mediated by exploration through self-locomotion at age 20 months. However, in the same study, spatial-relational object exploration at age 20 months did not predict spatial language. In a second study, the authors show that the former effect is unique to spatial language and does not extend to other linguistic domains such as the use of grammatical and lexical categories (Oudgenoeg-Paz *et al.*, 2016). Similarly, Marcinowski and Campbell (2017) have shown that children who showed more advanced exploration (seen as combining objects) at ages 10 to 14 months also understood more spatial words at age three years. Exploration skill was related only to spatial language and not to general language or cognitive skill. Together, these results suggest that the knowledge acquired by spatial exploration is uniquely predictive of spatial language development.

Finally, studies show that motor development and exploration change the verbal input children receive from caregivers. Playing with certain types of toys such as blocks that enable more elaborate combinations, elicits more spatial language input from caregivers (Ferrara *et al.*, 2011). This input is, in turn, longitudinally related to better spatial language (Pruden *et al.*, 2011). To summarize, like other aspect of spatial cognition, also spatial language appears to be learnt through ongoing perception-action loops enabling children to learn about spatial relations and elicit relevant input from caregivers.

Discussion and Conclusion

In this review we present evidence showing that exploration of the environment plays a central role in the early development of spatial memory, spatial orientation, spatial processing and spatial language. These findings include cross-sectional and longitudinal evidence and provide an indication that the relation is unique in the sense that specific kinds of exploration are related to development in specific cognitive domains. These findings are in line with the ecological approach to child development. In the next sections, we describe in turn the importance of such specificity of relationships for theory building and the variable developmental paths travelled by children with motor disabilities on the road to spatial cognition. Then we turn to highlight open questions regarding the nature of information obtained while exploring and what this means for spatial cognition and the importance of understanding how differences in the physical and social environment contribute to exploration and development.

The specificity of the relations is seen for example in the different effects of sitting and walking in the study of Oudgenoeg-Paz and colleagues (2015) and in the uniqueness of effects of exploration on spatial language in the work of Marcinowski and Campbell (2017) and Oudgenoeg-Paz and colleagues (2016). These results suggest that the relationships between exploration and spatial skills depend on the type of information obtained through each kind of exploratory activity. In other words, the relationships are grounded in the information structures present in the environment and the actions these structures afford in combination with children's action possibilities. Given the specificity of these associations, it seems unlikely that these developmental relationships can be reduced to a general maturation process. Children develop through many concrete experiences in their environment occurring over micro-time (i.e., seconds, minutes), leading to macro-level changes in development (i.e., months, years) – which is a central tenet of the dynamic systems approach to development (Smith & Thelen, 2003). Spatial cognition development depends on a manifold of concrete real-life interactions involving exploration that converge at some point to enable the 'emergence' of these skills (see Thelen & Smith, 1996 and Gibson, 1988 for a detailed description of this idea). The consistently emerging pattern of specific relations across exploratory activities, spatial skills and ages, calls for a larger scale investigation testing clear hypotheses about what relations are and are not expected both cross-sectionally and longitudinally.

In light of the findings reviewed, the question arises what these findings mean for children with motor disabilities? Is exploration necessary for the development of spatial cognition? The literature concerning children with motor disabilities falls beyond the scope of the current review. However, some evidence does suggest that children with motor delays due to Spina Bifida do show delays in their performance on spatial memory tasks (Campos *et al.*, 2009). However, other studies show that children with severe motor delays due to Spinal Muscular Atrophy do not show delays in spatial memory and spatial language. On the contrary, they even show precocious development in these domains (Rivière & Lécuyer, 2002; 2003; Rivière *et al.*, 2009). Thus, under certain conditions exploration as we see in typically developing children, involving engagement in self-produced locomotion, might not be necessary. It is likely that children with extreme delays in motor development find alternative ways to explore their environment to obtain information that is similar (though not identical) to the information obtained by typically developing children. These children might for example use their linguistic skills to get their social environment to perform exploratory actions for them. This might be termed exploration through a proxy (see also Oudgenoeg-Paz & Rivière, 2014). Further work is clearly needed to study the process of spatial cognitive development in these populations.

Open Questions

In order to fully understand the process through which exploration propels spatial cognition it is important to gain a thorough insight into the perceptual information children with varying motor skill level generate and receive in their daily lives across varying contexts. Initial work involving both the lab and the home setting (e.g., Karasik *et al.*, 2011; 2014; Kretch *et al.*, 2014) showed that the perceptual information children obtained while crawling dramatically differs from the perceptual information children obtained while walking. Most studies reviewed here did not specifically compare the effects of walking and crawling on spatial development. However, empirical evidence in related fields has shown that walking attainment changes exploration of the physical and social environment as walking children were shown to interact differently with objects and people compared to crawling children. Walking children, for example, carry objects more and initiate more joint engagement with parents while moving (Clearfield, 2011; Karasik *et al.*, 2011; Walle, 2016). These different interactions also elicit different types of verbal input from the social environment of children. Parents responded differently to actions made by stationary versus locomoting infants and actions made by crawling versus walking infants (Karasik *et al.*, 2014; Walla & Campos, 2014). Future work should study the difference in effects of crawling and walking attainment on spatial cognition and provide us with more detailed insights into the information children obtain while exploring in their daily lives. Note, however, that the measurement of everyday experiences at this level of detail poses a methodological challenge. In a recent review, Franchak (2020) suggests possible solutions to these challenges including for example light weight headcams to measure visual information and lightweight inertial sensors to document posture.

An additional factor to consider is the physical environment which children explore. Studies show for example that the use of practices that restrict movement varies between cultures. For example, in Tajikistan infants spend many hours per days restrained on their backs in a traditional cradle (Karasik *et al.*, 2018). Differences were also found between western cultures where, for example, Dutch infants spend far more time in the playpen compared to Israeli children that are more often placed on the floor and allowed to freely explore their environment (Oudgenoeg-Paz *et al.*, 2020). Other variations in the environment could come from factors such as the availability of materials (for example due to low income of the family; Bradley & Putnick, 2012) or the size and shape of the house families live in (e.g., Berger *et al.*, 2007). Another study showed that children produced more spatial language if they were allowed to interact with tangible toys that included varied shapes (Verdine *et al.*, 2019). In contrast, Cole and colleagues (2016) have shown that toddlers explore a room by walking the same amount of bouts of steps regardless of whether the room is full with objects to explore or completely empty. This suggests that, while the physical environment does play a role in facilitating and eliciting exploration, infants also actively engage in a type of locomotor exploration were the perception-action cycle mostly relies on proprioception. It is important to study in depth how the information obtained through exploration varies between children growing up in different environments and what implications these differences might have for their (spatial) cognitive development.

Besides the physical environment, the social environment is also a key factor to consider. With regard to the acquisition of spatial language (and language in general) it is clear that the input from the environment is crucial (e.g., Pruden *et al.*, 2011). Importantly, children's (motor) skills and exploration also play a role in directing this input. A study by Karasik and colleagues (2014) has shown that mothers of walking infants responded more often with action directives (e.g., "open it") to their infant's object sharing (defined as a "bid"), as compared to affirmations (e.g., "thank you") or descriptions (e.g., "a red box"). Further investigation showed that walking infants made more bids while locomoting, whereas crawling infants mostly made stationary bids. Mothers generally responded to moving bids with such action directives. While evidence for the role of the social environment exist mainly for spatial language, it seems likely that this environment also plays an important role in the development of other aspects of spatial cognition. Caregivers might encourage certain types of exploration and discourage others. However, empirical evidence in this field is still scarce and work is still needed to study the role of the social environment in shaping children's exploration and how this relates to further development.

To conclude, the current review shows that multiple studies with typically developing children provide compelling evidence for the role of active (spatial) exploration in the development of several spatial skills. It is important to note that empirical evidence shows that not all types of exploration are related to all types of spatial skills. Rather, the relationships between the different forms of exploration and the different spatial skills seem to be specific as they are dependent on the specific affordances children explore while engaging in different forms of exploration. As such, these findings provide support for the idea that spatial cognition is grounded in daily interactions between children and their environment.

References

Acredolo, L. P., Adams, A., & Goodwyn, S. W. (1984). The role of self-produced movement and visual tracking in infant spatial orientation. *Journal of Experimental Child Psychology*, *38*(2), 312-327.

Adolph, K. E. (2019). An ecological approach to learning in (not and) development. *Human Development*, *63*(3-4), 180-201. https://doi.org/10.1159/000503823

Adolph, K. E. (1997). Learning in the development of infant locomotion. *Monographs of the society for research in child development*, *62* (3, Serial No. 251).

Adolph, K. E., Eppler, M. A., Marin, L., Weise, I. B., & Clearfield, M. W. (2000). Exploration in the service of prospective control. *Infant Behavior and Development*, *23*(3-4), 441-460. https://doi.org/10.1016/S0163-6383(01)00052-2

Berger, S. E., Theuring, C., & Adolph, K. E. (2007). How and when infants learn to climb stairs. *Infant Behavior and Development*, *30*(1), 36-49. https://doi.org/10.1016/j.infbeh.2006.11.002

Bradley, R. H., & Putnick, D. L. (2012). Housing quality and access to material and learning resources within the home environment in developing countries. *Child Development*, *83*(1), 76-91. https://doi.org/10.1111/j.1467-8624.2011.01674.x

Campos, J. J., Anderson, D. I., & Telzrow, R. (2009). Locomotor experience influences the spatial cognitive development of infants with spina bifida. *Zeitschrift für Entwicklungspsychologie und Pädagogische Psychologie*, *41*(4), 181-188.

Campos, J. J., Anderson, D. I., Barbu-Roth, M. A., Hubbard, E. M., Hertenstein, M. J., & Witherington, D. (2000). Travel broadens the mind. *Infancy*, *1*(2), 149-219. https://doi.org/10.1207/S15327078IN0102_1.

Clearfield, M. W. (2004). The role of crawling and walking experience in infant spatial memory. *Journal of Experimental Child Psychology*, *89*(3), 214-241. https://doi.org/10.1016/j.jecp.2004.07.003

Clearfield, M. W. (2011). Learning to walk changes infants' social interactions. *Infant Behavior and Development*, *34*(1), 15-25. https://doi.org/10.1016/j.infbeh.2010.04.008

Cole, W. G., Robinson, S. R., & Adolph, K. E. (2016). Bouts of steps: The organization of infant exploration. *Developmental Psychobiology*, *58*(3), 341-354. https://doi.org/10.1002/dev.2137

Creem-Regehr, S. H., Gagnon, K. T., Geuss, M. N., & Stefanucci, J. K. (2013). Relating spatial perspective taking to the perception of other's affordances: Providing a foundation for predicting the future behavior of others. *Frontiers in Human Neuroscience*, *7*, 596. https://doi.org/10.3389/fnhum.2013.00596.

Feldman, A., & Acredolo, L. (1979). The effect of active versus passive exploration on memory for spatial location in children. *Child Development*, *50*(3) 698-704.

Ferrara, K., Hirsh-Pasek, K., Newcombe, N. S., Golinkoff, R. M., & Lam, W. S. (2011). Block talk: Spatial language during block play. *Mind, Brain, and Education*, *5*(3), 143-151.

Foreman, N., Foreman, D., Cummings, A., & Owens, S. (1990). Locomotion, active choice, and spatial memory in children. *Journal of General Psychology*, *117*, 215-232.

Franchak, J. M. (2020). The ecology of infants' perceptual-motor exploration. *Current Opinion in Psychology*, *32*, 110-114. https://doi.org/10.1016/j.copsyc.2019.06.035

Frick, A., & Möhring, W. (2013). Mental object rotation and motor development in 8- and 10-month-old infants. *Journal of Experimental Child Psychology*, *115*(4), 708-720. https://doi.org/10.1016/j.jecp.2013.04.001

Gibson, E. J. (1988). Exploratory behavior in the development of perceiving, acting, and the acquiring of knowledge. *Annual Review in Psychology*, *39*(1), 1-41.

Gibson, E. J., & Pick, A. D. (2000). *An ecological approach to perceptual learning and development*. Oxford University Press.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Houghton Mifflin, Reprinted 1986, Erlbaum.

Hazen, N. L. (1982). Spatial exploration and spatial knowledge: Individual and developmental differences in very young children. *Child Development*, *53*(3), 826-833.

Horobin, K., & Acredolo, L. P. (1986). The role of attentiveness, mobility history, and separation of hiding stages on Stage IV search behaviour. *Journal of Experimental Child Psychology*, *41*(1), 114-127.

Karasik, L. B., Tamis-LeMonda, C. S., & Adolph, K. E. (2011). Transition from crawling to walking and infant's actions with objects and people. *Child Development*, *82*(4), 1199-1209. https://doi.org/10.1111/j.1467-8624.2011.01595.x.

Karasik, L. B., Tamis-LeMonda, C. S., & Adolph, K. E. (2014). Crawling and walking infants elicit different verbal responses from mothers. *Developmental Science*, *17*(3), 388-395. https://doi.org/10.1111/j.1467-8624.2011.01595.x

Karasik, L. B., Tamis-LeMonda, C. S., Ossmy, O., & Adolph, K. E. (2018). The ties that bind: Cradling in Tajikistan. *PloS one*, *13*(10), article e0204428. https://doi.org/10.1371/journal.pone.0204428

Kermoian, R., & Campos, J. J. (1988). Locomotor experience: A facilitator of spatial cognitive development. *Child Development*, *59*(4), 906-917.

Kretch, K. S., Franchak, J. M., & Adolph, K. E. (2014). Crawling and walking infants see the world differently. *Child Development*, *85*(4), 1503-1518. https://doi.org/10.1111/cdev.12206

Landau, B., & Hoffman, J. E. (2005). Parallels between spatial cognition and spatial language: Evidence from Williams syndrome. *Journal of Memory and language*, *53*(2), 163-185. https://doi.org/10.1016/j.jml.2004.05.007

Libertus, K., & Violi, D. A. (2016). Sit to talk: relation between motor skills and language development in infancy. *Frontiers in Psychology*, *7*, 475. https://doi.org/10.3389/fpsyg.2016.00475

Marcinowski, E. C., & Campbell, J. M. (2017). Building on what you have learned: Object construction skill during infancy predicts the comprehension of spatial relations words. *International Journal of Behavioral Development*, *41*(3), 341-349. https://doi.org/10.1177/0165025416635283

Möhring, W., & Frick, A. (2013). Touching up mental rotation: Effects of manual experience on 6-month-old infants' mental object rotation. *Child Development*, *84*(5), 1554-1565. https://doi.org/10.1111/cdev.12065

Muentener, P., Herrig, E., & Schulz, L. (2018). The Efficiency of Infants' Exploratory Play Is Related to Longer-Term Cognitive Development. *Frontiers in Psychology*, *9*, 635. https://doi.org/10.3389/fpsyg.2018.00635

Mulder, H., Oudgenoeg-Paz, O., Hellendoorn, A., & Jongmans, M. J. (2017). How children learn to discover their environment: an embodied dynamic systems perspective on the development of spatial cognition. In A. Postma, & I. J. van der Ham (Eds.). *Neuropsychology of space: Spatial functions of the human brain* (pp. 309-360). Academic Press.

Mulder, H., Oudgenoeg-Paz, O., Verhagen, J., I. J. M. van der Ham, & Van der Stigchel, S. (2020). *Infant walking experience is related to the development of selective attention*. Manuscript submitted for publication.

Newcombe, N. S., Uttal, D. H., & Sauter, M. (2013). Spatial development. In P. Zelazo (Ed.), *Oxford handbook of developmental psychology* (Vol. 1, pp. 564-590). Oxford University Press.

Oudgenoeg-Paz, O., & Rivière, J. (2014). Self-locomotion and spatial language and spatial cognition: Insights from typical and atypical development. *Frontiers in Psychology*, *5*, 521. https://doi.org/10.3389/fpsyg.2014.00521

Oudgenoeg-Paz, O., Atun-Einy, O., & van Schaik, S. D. (2020). Two cultural models on infant motor development: Middle class parents in Israel and the Netherlands. *Frontiers in Psychology*, *11*, 119. https://doi.org/10.3389/fpsyg.2020.00119

Oudgenoeg-Paz, O., Leseman, P. P., & Volman, M. C. J. (2014). Can infant self-locomotion and spatial exploration predict spatial memory at school age? *European Journal of Developmental Psychology*, *11*(1), 36-48. https://doi.org/10.1080/17405629.2013.803470

Oudgenoeg-Paz, O., Leseman, P. P., & Volman, M. C. J. M. (2015). Exploration as a mediator of the relation between the attainment of motor milestones and the development of spatial cognition and spatial language. *Developmental Psychology*, *51*(9), 1241-1253. https://doi.org/10.1037/a0039572

Oudgenoeg-Paz, O., Volman, M. C. J., & Leseman, P. P. (2012). Attainment of sitting and walking predicts development of productive vocabulary between ages 16 and 28 months. *Infant Behavior and Development*, *35*(4), 733-736. https://doi.org/10.1016/j.infbeh.2012.07.010

Oudgenoeg-Paz, O., Volman, M. C., & Leseman, P. P. (2016). First steps into language? Examining the specific longitudinal relations between walking, exploration and linguistic skills. *Frontiers in Psychology*, *7*, 1458. https://doi.org/10.3389/fpsyg.2016.01458

Pelphrey, K. A., Reznick, J. S., Davis Goldman, B. D., Sasson, N., Morrow, J., Donahoe, A., & Hodgson, K. (2004). Development of visuospatial short-term memory in the second half of the 1st year. *Developmental Psychology*, *40(*5), 836-851. https://doi.org/:10.1037/0012-1649.40.5.836.

Pruden, S. M., Levine, S. C., & Huttenlocher, J. (2011). Children's spatial thinking: Does talk about the spatial world matter? *Developmental Science*, *14*(6), 1417-1430. https://doi.org/10.1111/j.1467-7687.2011.01088.x

Rivière, J., & Lécuyer, R. (2002). Spatial cognition in young children with spinal muscular atrophy. *Developmental Neuropsychology*, *21*(3), 273-283. https://doi.org/10.1207/S15326942DN2103_4

Rivière, J., & Lécuyer, R. (2003). The C-not-B error: a comparative study. *Cognitive Development*, *18*(3), 285-297. https://doi.org/10.1016/S0885-2014(03)00003-0

Rivière, J., Lécuyer, R., & Hickmann, M. (2009). Early locomotion and the development of spatial language: Evidence from young children with motor impairments. *European Journal of Developmental Psychology*, *6*(5), 548-566. https://doi.org/10.1080/17405620701345712

Schwarzer, G., Freitag, C., Buckel, R., & Lofruthe, A. (2013). Crawling is associated with mental rotation ability by 9-month-old infants. *Infancy*, *18*(3), 432-441. https://doi.org/10.1111/j.1532-7078.2012.00132.x.

Smith, L. B., & Thelen, E. (2003). Development as a dynamic system. *Trends in Cognitive Sciences*, *7*(8), 343-348. https://doi.org/:10.1016/S1364-6613(03) 00156-6

Smith, L. B., Thelen, E., Titzer, R., & McLin, D. (1999). Knowing in the context of acting: The task dynamics of the A-not-B error. *Psychological Review*, *106*(2), 235-260.

Smith, L., & Gasser, M. (2005). The development of embodied cognition: Six lessons from babies. *Artificial Life*, *11*(1-2), 13-29.

Soska, K. C., & Adolph, K. E. (2014). Postural position constrains multimodal object exploration in infants. *Infancy*, *19*(2), 138-161. https://doi.org/10.1111/infa.12039

Thelen, E., & Smith, L. B. (1996). *A dynamic system's approach to the development of cognition and action*. Bradford Books/MIT Press.

van den Brink, D., & Janzen, G. (2013). Visual spatial cue use for guiding orientation in two-to-three-year-old children. *Frontiers in Psychology*, *4*, 904. https://doi.org/10.3389/fpsyg.2013.00904

Verdine, B. N., Zimmermann, L., Foster, L., Marzouk, M. A., Golinkoff, R. M., Hirsh-Pasek, K., & Newcombe, N. (2019). Effects of geometric toy design on parent–child interactions and spatial language. *Early Childhood Research Quarterly*, *46*, 126-141. https://doi.org/10.1016/j.ecresq.2018.03.015

Walle, E. A. (2016). Infant social development across the transition from crawling to walking. *Frontiers in Psychology*, *7*, 960. https://doi.org/10.3389/fpsyg.2016.00960

Walle, E. A., & Campos, J. J. (2014). Infant language development is related to the acquisition of walking. *Developmental Psychology*, *50*(2), 336. https://doi.org/10.1037/a0033238

Wechsler, D. (2002). *Wechsler Preschool and Primary Scale of Intelligence – Third Edition (WPPSI–III)*. Pearson/PsychCorp.