Current Directions in Psychological Science
2014, Vol. 23(6) 439–445

DOI: 10.1177/0963721414549751
cdps.sagepub.com

Development of Spatial-Numerical Associations

Koleen McCrink[1] and John E. Opfer[2]
[1]Barnard College, Columbia University, and [2]The Ohio State University

Abstract
Links between spatial and numerical thinking are well established in studies of adult cognition. Here, we review recent research on the origins and development of these links, with an emphasis on the formative role of experience in typical development and on the theoretical insights to be gained from infant cognition. This research points to three important influences on the development of spatial-numerical associations: innate mechanisms linking space and nonsymbolic number, gross and fine motor activity that couples spatial location to both symbolic and nonsymbolic number, and culturally bound activities (e.g., reading, writing, and counting) that shape the relationship between spatial direction and symbolic number.

Keywords
cognitive development, spatial cognition, numerical cognition, spatial-numerical associations

Spatial associations with abstract concepts—such as those involved when thinking of future events as occurring in a forward direction (Boroditsky, 2000), power as ascending vertically (Schubert, 2005), or numbers as increasing from left to right (Hubbard, Piazza, Pinel, & Dehaene, 2005)—permeate our mental life. Today, research in developmental psychology is beginning to shed new light on where these associations come from, how they change over time, and what functions they might serve.

In this review, we will examine the development of spatial-numerical associations, that is, how the parts of the mind that underlie spatial and numerical ability interact throughout development. A central question surrounding the development of spatial-numerical associations concerns the role of experience in shaping the mental number line. On one side is the theory that brain networks specialized for space and number are intertwined at birth; experience, in this view, *differentiates* these streams of information. One version of this view is Walsh's (2003) theory of magnitude, in which space, time, and number are represented at birth by a single system that calculates a generic sense of quantity, or "how much" (rather than discrete number per se). The competing theory proposes that representations of space and number are distinct at birth and related throughout development; experience, in this view, *integrates* these streams of information by highlighting the underlying similarity of space and number through repeated exposure, linguistic prompts, and motor plans (for a review, see Lourenco & Longo, 2011).

These two theories lead to quite different expectations about the course of development. If experience creates spatial-numerical associations, we should find that young children (ideally newborns, a population with minimal experience in the world) harbor no expectations about whether numeric value is linked to spatial extent, a particular spatial direction (e.g., leftward vs. rightward), or some combination of the two. On the other hand, if spatial-numerical associations exist because space and number are not initially differentiated, then it should be possible to find very young children who have symmetric expectations about space and number (i.e., expectations that spatial extent, direction, or their combination predicts numeric value, or vice versa) and appear to generalize one space-number pairing to another space-number pairing.

Corresponding Author:
Koleen McCrink, Department of Psychology, Barnard College, Columbia University, 3009 Broadway, New York, NY 10027
E-mail: kmccrink@barnard.edu

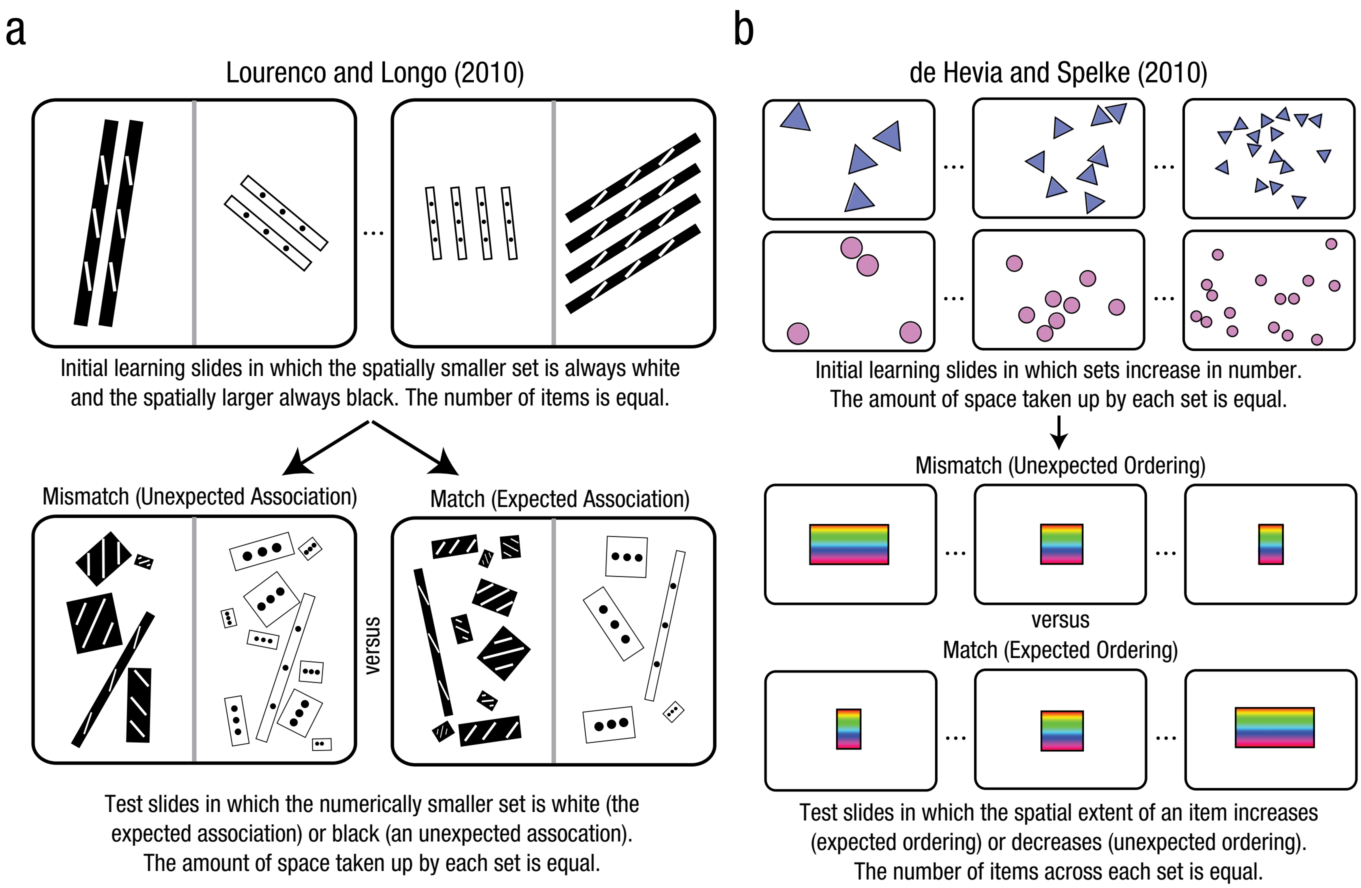

Fig. 1. Schematic of habituation and test stimuli used by (a) Lourenco and Longo (2010) and (b) de Hevia and Spelke (2010) to demonstrate early preverbal spontaneous associations between spatial and numerical representations in infants.

Innate Mechanisms Linking Space and Nonsymbolic Number

Might the links between space and number develop from the innate design characteristics of the brain? Evidence addressing this question has come from a wide array of sources, including behavioral research on learning biases in human infants, neural recordings of nonhuman primates, and studies of animals reared without previous visual experience.

First, do human infants spontaneously relate spatial and numerical dimensions? To address this issue, Lourenco and Longo (2010) taught 9-month-olds an arbitrary rule across either a spatial or a numerical dimension to discover whether they spontaneously applied the rule to the other (untrained) dimension (Fig. 1a). For example, infants were trained with the rule that objects in two sets containing different numbers of objects—such as 2 and 4—had unique characteristics: The less-numerous set was always white and the more-numerous set always black. Infants easily learned this rule and generalized it to a new set of numerical arrays (e.g., 5 and 10), looking longer during test if the rule had been violated (e.g., if the less numerous set was black and the more numerous white). More intriguingly, infants generalized this rule to sets of new sizes as well. Shown a test slide that had two sets of two objects, infants expected the previous rule to hold, looking longer if the set that had a smaller overall size was black and the larger-sized set was white. Another group of infants exhibited similar prowess at this task when the learning dimension was size based and the testing dimension number based. Thus, infants applied a learned rule involving "more than" and "less than" across spatial and numerical dimensions symmetrically, even when trained on only one dimension.

If infants spontaneously relate number and size, how do they relate number to other spatial dimensions (e.g., length) and nonspatial dimensions (e.g., brightness)? To address this, de Hevia and Spelke (2010) showed 8-month-olds slides depicting an increasing or decreasing number of objects (e.g., a set of circles that increased in number). As infants watched these slides, their looking times decreased—a process referred to as *habituation*—and they were then shown test slides of a spatial stimulus (a line) that either increased or decreased in length (Fig. 1b). Infants who were initially exposed to an increasing number of objects looked longer at test slides showing a shrinking line, whereas infants who habituated to a decreasing number of objects looked longer at a growing line.

More importantly, the infants could readily learn a consistent positive relation between number and line length, but could not learn a negative relation. Indeed, when infants were shown slides illustrating a positive relation between numerical and spatial quantity (e.g., numerous arrays paired with long lines), they spontaneously preferred positive spatial-numerical pairings over negative pairings (e.g., sparse arrays paired with long lines). In a series of follow-up studies, de Hevia and Spelke (2013) found that although infants could learn number-brightness relations if they were shown repeated pairings, this link was more tenuous than that between number and space: Infants did not spontaneously relate "more" to "brighter," and there was no clear distinction between the enhanced learning of positive compared with inverse relations as had been found with number-space pairings.

Recent work by de Hevia, Izard, Coubart, Spelke, and Streri (2014) has established that even newborns are selectively sensitive to positive relationships between space and number. Thus, we see that infants not only can learn spatial-numerical associations but also already prefer a "numerically greater goes with spatially larger" association to a "numerically greater goes with spatially smaller" association, and apply this rule preferentially to spatial dimensions. Intriguingly, preschoolers' abilities to link space and number seem no more flexible than those of infants. De Hevia, Vanderslice, and Spelke (2012) found that preschoolers also reliably matched number and space (e.g., matching less numerous arrays with shorter lines and more numerous arrays with longer lines), although they failed to do so when stimuli exhibited a negative relation. Further, these preschoolers also failed to match number with another continuous dimension, brightness.

Together, the pattern that emerges from these studies is one in which newborns, infants, and very young children spontaneously associate spatial and numerical information, but this pairing is biased in a manner consistent with a number line, wherein the space between two numbers increases with their difference in value. Infants' first bias is for *spatial magnitude*; number and space are more readily associated than number and brightness. Infants' second bias is for preserving *congruent magnitude*; infants more readily learn to associate "more" with "more" and "less" with "less" than they can learn to associate "more" with "less." Because it is difficult to explain newborns' biases as a result of their experience with the world, these results are consistent with a developmental trajectory in which space and number are integrated at birth and become distinct. On the other hand, direct evidence for the proposed unfolding of this differentiation account is lacking. For example, no evidence exists that experience makes it *more* difficult for children to transfer from space to number (or vice versa)—a testable prediction from this theory.

What mechanisms might link space and number in newborns? Insights from studies of animal learning shed light on this question. In one such study, Tudusciuc and Nieder (2007) required monkeys to indicate whether two line lengths or numerical magnitudes matched, and they recorded the electrical activity of 400 single brain cells in and around the primate version of the intraparietal sulcus—a brain region that in humans encodes both symbolic and nonsymbolic number. The authors found three distinct types of neurons in this region: neurons that encoded number exclusively, neurons that encoded space exclusively, and neurons that encoded both space and number. These results yield an existence proof that, for species along the same limb of the evolutionary tree as humans, space and number share a common neural code, but they leave open the possible role of experience in linking them.

Studies of dark-reared newborn chicks have addressed the role of experience more directly (Rugani, Kelly, Szelest, Regolin, & Vallortigara, 2010), though their results speak to the relation of number to spatial position rather than spatial extent. During a training phase, hatchlings were shown 16 containers extending vertically in front of them, and either the 4th or the 6th container was reinforced with food. At test, the experimenters rotated the line of containers horizontally and measured where the hatchlings pecked. Remarkably, the birds exhibited a clear preference to peck at the 4th and 6th locations *from the left*, indicating (a) an ability to approximately encode 4 and 6 items and (b) a preference for asymmetric encoding of the order of items starting with the left side of space. These results are not a quirk of the avian brain; monkeys given a similar task show a similar preference for encoding number starting with the left side of space (Drucker & Brannon, 2014), and chimpanzees trained to order the Arabic numerals 1 through 9 also show a spontaneous preference for 9 appearing on the right and 1 appearing on the left (Adachi, 2014). These findings are suggestive of a spontaneous and unlearned link between spatial extent and number, as well as spatial location and numeric order, although whether humans have inherited these links was not addressed in these studies.

Influence of Motor Behavior in Refining Spatial-Numerical Associations

In addition to evidence for innate mechanisms linking space and number, there is also growing evidence that children's motor behavior refines their preexisting spatial-numerical associations. For example, although infants seem to expect number and space to be congruently associated, mappings between number and space become more linear (rather than logarithmic) with age and experience (Siegler & Opfer, 2003). One reason motor behavior might refine spatial-numerical associations in this way is that control of motor behavior (e.g., picking up a full vs. empty suitcase) requires a quantitative calibration of distinct magnitudes, one of which is potentially spatial and the other numerical.

A good illustration of this potential benefit has come from U. Fischer, Moeller, Bientzle, Cress, and Nuerk (2011). They found that kindergarteners' ability to estimate the positions of numbers on number lines benefited more from practice using full-body movement on a physical number line than from practice using a similar, computer-based number line. Another example of this physical link between space and number is the finger-counting behavior observed in very young children. Theoretically, the one-to-one correspondence between fingers and objects in a set may act as a useful tool to map something symbolic (a list of number words) to something nonsymbolic (an array of physical objects or fingers). Although an influential relationship between the hands and mathematical skills exists in adulthood ("manumerical cognition"; M. H. Fischer & Brugger, 2011), more developmental data is needed to determine whether finger counting *causes* spatial-numerical associations. If anything, research on early finger counting has shown that children start with small numbers on their right hand (because of dominant handedness; Sato & Lalain, 2008; for a review, see Previtali, Rinaldi, & Girelli, 2011).

The visual system is sometimes proposed as yet another "embodied" route through which spatial-numerical associations develop, and there are several noted interactions between the visual system and spatial-numerical associations in adulthood. For example, adults asked to randomly generate numbers will look left when they provide small numbers and right when they provide large numbers (Loetscher, Bockisch, Nicholls, & Brugger, 2010), and the part of the brain that is active when making horizontal eye movements—as if along a number line—is recruited when people calculate outcomes to addition or subtraction problems (Knops, Thirion, Hubbard, Michel, & Dehaene, 2009). By preschool, children comparing numbers respond more quickly to small numbers appearing on the left side of their visual field and large numbers appearing on the right side than the reverse (Patro & Haman, 2012). Certain types of visual attention are linked to spatial-numerical associations by the time children enter into formal arithmetic instruction; Knops, Zitzmann, and McCrink (2013) found that 6- and 7-year-olds who are more proficient at switching their attention from an irrelevant to a relevant location exhibited more adultlike spatial-numerical associations.

Could the developing visual system act as an interface between spatial and numerical representations in childhood, especially with respect to the lateralization of spatial-numerical associations into a conventional number line (e.g., small = left, large = right)? Perhaps most telling is work on visually impaired individuals, who do not obtain some types of spatial-numerical associations by the same age as sighted individuals (Bachot, Gevers, Fias, & Roeyers, 2005). However, Crollen, Dormal, Seron, Lepore, and Collignon (2013) found that early-blind individuals still possessed spatial-numerical associations, although they mapped numbers to their personal space (e.g., they associated small numbers with their left hand, even when that left hand was crossed to their right side) instead of external space (as in the case of sighted adults, who associate small numbers with the left side of their visual field). This suggests that damage to the visual system in development alters the nature and timeline of spatial-numerical associations, but not their overall presence.

Influence of Cultural Activity in Linking Space to Symbolic Number

A final influence on the development of spatial-numerical associations is the culturally specific experience that children encounter at home and in school. Indeed, the first explanations of spatial-numerical associations were cultural, pointing to late-developing and increasingly automatized reading and writing behaviors as the founding link between spatial and numerical processing. Dehaene, Bossini, and Giraux's (1993) seminal set of experiments on spatial-numerical associations in adulthood found that length of time spent in a Westernized society correlated with the degree to which the mental number line was oriented in a left-to-right fashion, leading the authors to speculate that spatial-numerical associations were determined by the direction of writing. In another study, Berch, Foley, Hill, and Ryan (1999) found that a classic form of spatial-numerical associations was late emerging (around 9 years) and interpreted this finding as reflecting formal schooling practices. Moreover, illiterate populations do not show classic forms of spatial-numerical associations (Shaki, Fischer, & Gobel, 2012; Zebian, 2005).

One problem with the idea that spatial-numerical associations come from reading practice is that even pre-reading preschoolers show spatial-numerical associations (Opfer, Thompson, & Furlong, 2010). For example, when searching for an object in the fourth of five compartments, preschoolers were faster and more accurate when the compartments had been labeled from left to right than from right to left (Fig. 2a: McCrink, Shaki, &

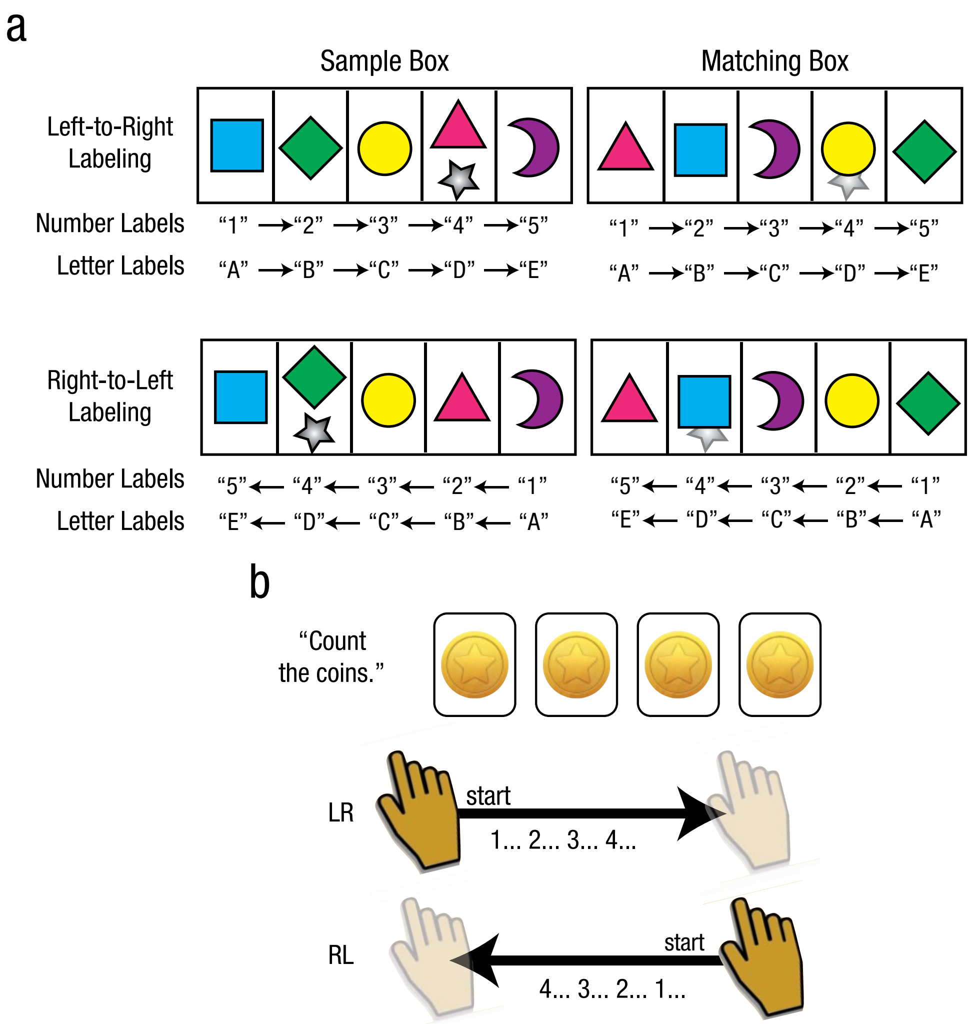

Fig. 2. Examples of paradigms used to assess different types of spatial-numerical associations in early childhood. The schematic shown in panel (a) illustrates a task used in Opfer, Thompson, and Furlong (2010) and Opfer and Furlong (2011) and adapted by McCrink, Shaki, and Berkowitz (2014). In this task, preschoolers hear several marked spatial compartments labeled numerically or alphabetically. They are then shown a prize hidden in one of the compartments of the sample box and asked to retrieve it from the matching box. U.S. preschoolers, especially those who count from left to right, perform better when labels are left to right. Israeli preschoolers perform the task better when the labels are presented right to left. The schematic shown in panel (b) illustrates a task used in Shaki, Fischer, and Gobel (2012) and Opfer et al. (2010). When asked to count an array, preschoolers in England and the United States do so from left to right, as do Israeli preschoolers. Preschoolers from Palestine count from right to left. After the completion of formal schooling, children and adults whose cultures maintain a consistent reading direction for numbers and letters (i.e., from left to right in England and from right to left in Palestine) exhibit the same counting direction. Israeli children and adults, whose culture reads letters from right to left and numbers from left to right, exhibit no such counting-direction preference. LR = left to right, RL = right to left.

Berkowitz, 2014; Opfer et al., 2010). Further, this benefit was mediated not by sensitivity to reading direction but by children's counting behavior; those who spontaneously counted objects in a left-to-right manner were most likely to benefit when presented with left-to-right labels (Opfer & Furlong, 2011).

While directional biases in counting do appear before children learn to read and write, they are also impacted by schooling. In one study of British, Palestinian, and Israeli children and adults, Shaki et al. (2012: Fig. 2b) found that the youngest children in all groups counted with some directional preference, and this preference was later exacerbated or eliminated depending on the nature of their formal schooling. Preschoolers growing up in England, for example, preferred left-to-right counting, whereas those who grew up in Palestine and Israel counted from right to left. For both Palestinian and British children, these counting patterns grew more prevalent after they entered into an educational system in which numbers and words were written in the same direction. However, Israeli children received a mixed message at the advent of schooling—numbers and words were read in differing directions. As a result, their counting shifted from directional to nondirectional.

Taken together, developmental research suggests that individual children—like the dark-reared chicks in Rugani et al. (2010)—are highly likely to show directional biases in their spatial-numerical associations, but these directional biases come to conform to cultural conventions (e.g., the left-to-right bias in England and the right-to-left bias in Palestine) as a result of cultural biases in prereading activities (e.g., counting) and reading habits as well. Still other sources of these biases may include exposure to linguistic metaphors (e.g., hearing "the winter is behind us"; Nuñez, 2011), though these influences remain to be tested.

Conclusions

From the earliest measurement tools, to the Cartesian coordinates of the plane, to the proof of Fermat's Last Theorem, the history of mathematics has been advanced by links between space and number (Hubbard et al., 2005). The growth of mathematical knowledge in children as well is predicted by the ability to map numbers to space (Booth & Siegler, 2008; Gunderson, Ramirez, Beilock, & Levine, 2012), a finding that has led to successful interventions designed to train children on space-number relations (Ramani & Siegler, 2011).

In this review, we have examined evidence on the origins of spatial-numerical associations, as well as their refinement with experience. Our review points to an early and potentially innate bias to encode number and space in an undifferentiated manner, which makes the acquisition of a mental number line—in which number increases congruently with space—probable, but (at least in humans) with no particular directional bias (e.g., a "small = left, large = right" bias) and without space and number being associated linearly. Beyond these origins, motor activities (e.g., finger and eye movements involved in counting) appear to calibrate spatial-numerical associations, but these activities differ among cultures, such that some count from right to left and others from left to right. Seen in this way, the development of spatial-numerical associations reflects a pattern seen in many domains: Evolution attunes expectations from birth, and enculturation exploits and shifts these expectations as children adapt to their cultural environment.

Recommended Reading

Dehaene, S., Bossini, S., & Giraux, P. (1993). (See References). A historical classic in the field of spatial-numerical cognition that established the Spatial-Numerical Association of Response Codes effect.

de Hevia, M. D., Girelli, L., & Macchi Cassia, V. (2012). Minds without language represent number through space: Origins of the mental number line. *Frontiers in Psychology*, *3*, Article 466. doi:10.3389/fpsyg.2012.00466. An article that provides an extensive discussion of the evidence for a mental number line in preverbal and nonverbal organisms.

Haun, D., Jordan, F., Vallortigara, G., & Clayton, N. (2010). Origins of spatial, temporal, and numerical cognition: Insights from comparative psychology. *Trends in Cognitive Sciences*, *14*(12), 552–560. An article that provides a thoughtful review of what psychological research on animals can tell us about fundamental representations of number and space.

Opfer, J. E., Thompson, C. A., & Furlong, E. E. (2010). (See References). A representative study that illustrates original research on the presence and ramifications of spatial-numerical associations in preschoolers.

Previtali, P., Rinaldi, L., & Girelli, L. (2011). (See References). A review that discusses what is known about the development of finger counting and its role in the development of spatial-numerical associations.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Funding

Support for the composition of this manuscript was provided by National Institute of Child Health and Human Development Grant 1R15HD065629-01 to K. McCrink.

References

Adachi, I. (2014). Spontaneous spatial mapping of learned sequence in chimpanzees: Evidence for a SNARC-like effect. *PLoS ONE*, *9*(3), e90373. Retrieved from http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0090373

Bachot, J., Gevers, W., Fias, W., & Roeyers, H. (2005). Number sense in children with visuospatial disabilities: Orientation of the mental number line. *Psychology Science*, *47*, 172–183.

Berch, D. B., Foley, E. J., Hill, R. J., & Ryan, P. M. (1999). Extracting parity and magnitude from Arabic numerals: Developmental changes in number processing and mental representation. *Journal of Experimental Child Psychology*, *74*, 286–308.

Booth, J. L., & Siegler, R. S. (2008). Numerical magnitude representations influence arithmetic learning. *Child Development*, *79*, 1016–1031.

Boroditsky, L. (2000). Metaphoric structuring: Understanding time through spatial metaphors. *Cognition*, *75*, 1–28.

Crollen, V., Dormal, G., Seron, X., Lepore, F., & Collignon, O. (2013). Embodied numbers: The role of vision in the development of number-space interactions. *Cortex*, *49*, 276–283.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representations of parity and number magnitude. *Journal of Experimental Psychology: General*, *123*, 371–396.

de Hevia, M. D., Izard, V., Coubart, A., Spelke, E., & Streri, A. (2014). Representations of space, time, and number in neonates. *Proceedings of the National Academy of Sciences, USA*, *111*, 4809–4813. doi:10.1073/pnas.1323628111

de Hevia, M. D., & Spelke, E. S. (2010). Number-space mapping in human infants. *Psychological Science*, *21*, 653–660.

de Hevia, M. D., & Spelke, E. S. (2013). Not all continuous dimensions map equally: Number-brightness mapping in human infants. *PLoS ONE*, *8*(11), e81241. Retrieved from http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0081241

de Hevia, M. D., Vanderslice, M., & Spelke, E. S. (2012). Cross-dimensional mapping of number, length and brightness by preschool children. *PLoS ONE*, *7*(4), e35530. Retrieved from http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0035530

Drucker, C. B., & Brannon, E. M. (2014). Rhesus monkeys (*Macaca mulatta*) map number onto space. *Cognition*, *132*, 57–67.

Fischer, M. H., & Brugger, P. (2011). When digits help digits: Spatial–numerical associations point to finger counting as prime example of embodied cognition. *Frontiers in Psychology*, *2*, Article 260. Retrieved from http://journal.frontiersin.org/Journal/10.3389/fpsyg.2011.00260/full

Fischer, U., Moeller, K., Bientzle, M., Cress, U., & Nuerk, H.-C. (2011). Sensori-motor spatial training of number magnitude representation. *Psychonomic Bulletin & Review*, *18*, 177–183.

Gunderson, E. A., Ramirez, G., Beilock, S. L., & Levine, S. C. (2012). The relation between spatial skill and early number knowledge: The role of the linear number line. *Developmental Psychology*, *48*, 1229–1241.

Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number and space in parietal cortex. *Nature Reviews Neuroscience*, *6*, 435–448.

Knops, A., Thirion, B., Hubbard, E. M., Michel, V., & Dehaene, S. (2009). Recruitment of an area involved in eye movements during mental arithmetic. *Science*, *324*, 1583–1585.

Knops, A., Zitzmann, S., & McCrink, K. (2013). Examining the presence and determinants of operational momentum in childhood. *Frontiers in Psychology*, *4*, Article 325. Retrieved from http://journal.frontiersin.org/Journal/10.3389/fpsyg.2013.00325/full

Loetscher, T., Bockisch, C., Nicholls, M., & Brugger, P. (2010). Eye position predicts what number you have in mind. *Current Biology*, *20*, R264–R265.

Lourenco, S. F., & Longo, M. R. (2010). General magnitude representation in human infants. *Psychological Science*, *21*, 873–881.

Lourenco, S. F., & Longo, M. R. (2011). Origins and development of generalized magnitude representation. In S. Dehaene & E. Brannon (Eds.), *Space, time, and number in the brain: Searching for the foundations of mathematical thought* (pp. 225–244). New York, NY: Academic Press.

McCrink, K., Shaki, S., & Berkowitz, T. (2014). Culturally driven biases in preschoolers' spatial search strategies for ordinal and non-ordinal dimensions. *Cognitive Development*, *30*, 1–14.

Nuñez, R. (2011). No innate number line in the human brain. *Journal of Cross-Cultural Psychology*, *42*, 651–668.

Opfer, J. E., & Furlong, E. E. (2011). How numbers bias preschoolers' spatial search. *Journal of Cross-Cultural Psychology*, *42*, 682–695.

Opfer, J. E., Thompson, C. A., & Furlong, E. E. (2010). Early development of spatial-numeric associations: Evidence from spatial and quantitative performance of preschoolers. *Developmental Science*, *13*, 761–771.

Patro, K., & Haman, M. (2012). The spatial-numerical congruity effect in preschoolers. *Journal of Experimental Child Psychology*, *111*, 534–542.

Previtali, P., Rinaldi, L., & Girelli, L. (2011). Nature or nurture in finger counting: A review on the determinants of the direction of number-finger mapping. *Frontiers in Psychology*, *2*, Article 363. Retrieved from http://journal.frontiersin.org/Journal/10.3389/fpsyg.2011.00363/abstract

Ramani, G. B., & Siegler, R. S. (2011). Playing linear numerical board games promotes low-income children's numerical development. *Developmental Science*, *11*, 655–661.

Rugani, R., Kelly, D. M., Szelest, I., Regolin, L., & Vallortigara, G. (2010). Is it only humans that count from left to right? *Biology Letters*, *6*, 290–292.

Sato, M., & Lalain, M. (2008). On the relationship between handedness and hand-digit mapping in finger counting. *Cortex*, *44*, 393–399.

Schubert, T. (2005). Your highness: Vertical positions as perceptual symbols of power. *Journal of Personality and Social Psychology*, *89*, 1–21.

Shaki, S., Fischer, M., & Gobel, S. (2012). Direction counts: A comparative study of spatially directional counting biases in cultures with different reading directions. *Journal of Experimental Child Psychology*, *112*, 275–281.

Siegler, R. S., & Opfer, J. E. (2003). The development of numerical estimation: Evidence for multiple representations of numerical quantity. *Psychological Science*, *14*, 237–243.

Tudusciuc, O., & Nieder, A. (2007). Neuronal population coding of continuous and discrete quantity in the primate posterior parietal cortex. *Proceedings of the National Academy of Sciences, USA*, *104*, 14513–14518.

Walsh, V. (2003). A theory of magnitude: Common cortical metrics of time, space, and quantity. *Trends in Cognitive Sciences*, *7*, 483–488.

Zebian, S. (2005). Linkages between number concepts, spatial thinking, and directionality of writing: The SNARC effect and the reverse SNARC effect in English and Arabic monoliterates, biliterates, and illiterate Arabic speakers. *Journal of Cognition and Culture*, *5*, 165–190.