How to Improve Spatial and Numerical Cognition with a Game-Based and Technology-Enhanced Learning Approach

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Abstract. In this paper, the connection between spatial and numerical cognition is highlighted and some applications to improve them are discussed. Indeed, in children, it is possible to promote numerical cognition, which is the base of mathematical cognition and academic achievement in later years, by strengthening their natural endowment to deal both with numerical stimuli and spatial stimuli.

Together with a brief review about spatial and numerical cognition, two tools that are meant to improve them with a Game-based and Technology enhanced approach are reported.

Keywords: Numerical cognition · Spatial cognition · Game-based learning · Technology-enhanced learning · Cognitive development

1 Introduction

Spatial and numerical cognition represent two of the four core knowledge systems at the foundation of human knowledge [44]. They are strictly connected with many issues that are relevant in different branches of research, including cognitive development.

Studying the development of spatial and numerical skills can be the starting point of relevant applications to educational context for geometry, science [26], mathematics, but also music [25].

The importance of spatial and numerical cognition is evident if we consider the developmental pathways that lead from the basic abilities that can be observed in human beings since the very first moment of their lives to the formal education in school context. Indeed, even if there is a common basis to start from, many different possible outcomes can be observed, including notable differences in math achievement at difference age, between genders [43] and in different cultures [46].

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These differences cannot be explained by disparity in natural endowment and are therefore likely to depend on other cultural and socio-cognitive factors, for example related to education methodology.

What we propose in this paper is a twofold startegy to improve numerical cognition and, possibly, the later school achievement in math, by addressing directly numerical cognition and by improving numerical skills through spatial cognition. Moreover we propose to adopt an approach relying on Game-based learning and Technology Enhanced learning to improve spatial and numerical cognition in an effective and involving way. In particular we describe two tools that aim at improving numerical and spatial cognition: Velocicards and Flatlandia creatures.

2 Spatial and Numerical Cognition

Human beings, as well as the other species are able to deal with numerical and spatial information without being instructed to do so. This indicates that there are some abilities that are innate and some others that can be acquired by the proper instruction, especially in human beings. This natural predisposition can be the basis of future academic abilities: an intervention on them can affect later achievement in school context.

2.1 Numerical Cognition

Considering numerical cognition, many evidence suggest that human infants possess an intuitive sense of number, the so-called number sense [6]. It is connected with the Approximate Number System (ANS) [14,16]: a cognitive system that supports the estimation of the magnitude of a group with more than four elements without relying on language or symbols, together with the parallel individuation system, or object tracking system for smaller magnitudes. Number sense in infancy predicts math skills in childhood. In the study by Starr and colleagues [45], we find the evidence that the number sense, before language acquisition, "may serve as a developmental building block for the uniquely human capacity for mathematics". These authors show that the performance on numerical preference scores at 6 months of age is correlated with math test scores at 3.5 years of age. This indicates that number sense may facilitate the acquisition of numerical symbols and mathematical abilities.

This evidence supports the theory of innate numerical abilities [3,15], according to which humans have, since the first of life, innate numerical skills to classify small sets of elements (4–5 items), and to distinguish in a rapid and accurate way a small amount of objects and elements, an ability called subitizing [20]. Only later, the culture teaches how to use this mathematical expertise in a more advanced manner. The study by Starr and colleagues goes a step forward, indicating that a stronger number sense predicts later numerical abilities, opening the way to the chance to foresee educational intervention which trains and strengthens the number sense to improve mathematical achievement in later years, as we will see in next section.

2.2 Spatial Cognition

Spatial competence undoubtedly represent a key competence for human adaptation [28]. Indeed spatial knowledge allows to represent elements in the world around and it has a huge adaptive value from every animals who moves in an environment, as they have to organize their action according to their spatial world.

This is true also for artificial agents: simulated or real robots can acquire the competence to act in the environment, only if they possess some kind of representation of the space around them, deriving from their perception [23,24,31]. In analogy with what we have described about numerical cognition, human children have also a predisposition to treat spatial information. For example, Huttenlocher and colleagues [18] show that the basic framework for coding location is present early in life and later development allows to increase this initial ability by organizing a broader range of bounded spaces.

2.3 The Connection Between Spatial and Numerical Cognition

Many studies have underlined the strong connection between spatial and numerical cognition. There is a wide literature on spatial associations during number processing which correlates these two core knowledge. One notable findings is the SNARC effect, spatial numerical association of response codes [9]. This effect consists in the fact that small numbers are reacted to faster with the left hand, large numbers with the right hand and gives a strong witness of this connection [49]. Moreover Fischer and Shaki [13] describe spatial biases found for single digits and pairs of numbers and numbers can be represented by humans on a logarithmic number line [8].

Another interesting effect that connects spatial and numerical cognition is the NIPE effect [30,32,39]. This effect [11], Number Interval Position Effect has been observed in the mental bisection of number intervals both in adults and in children. A systematic error bias in the subjective midpoint of number intervals is found: for intervals of equal size there is a shift of the subjective midpoint towards numbers higher than the true midpoint for intervals at the beginning of decades while for intervals at the end of decades the error bias is directionally reversed towards numbers lower than the true midpoint. This trend of the bisection error is recursively present across consecutive decades.

3 Spatial and Numerical Cognition in Education

Spatial and numerical cognition are not only crucial in adaptation process, but they also are relevant building blocks for human children and adolescents in school context, as hinted at in the introduction.

The pre-requisites on maths are important predictors of school achievement and success. The school readiness is a multidimensional concept that identifies the competences that a child needs before entering school [42]. Crucial indicators are the pre-requisites of learning, knowledge and abilities that develop before acquiring reading, writing and calculation skills and valuable up to preschool years [40]. Literature highlights consistently the importance of pre-requisites of calculation for the success in primary school and beyond [17,21,38].

Pre-requisites and later achievement connection has threats and opportunities. The transition between pre-requisites and advanced math skills can be problematic as it implies a switch from embodied elements to symbolic one. After kindergarten where children use their fingers and physical objects to count, the learning approach strategy soon becomes abstract, mainly relying on working memory [1]. Whereas some children are able to follow this step, some others do not and this can generate difficulties at school. On the opportunity side, if pre-requisites are strengthened also later achievement can be improved, a relevant intervention chance.

Also spatial and numerical cognition connection can be exploited to improve math achievement. Many studies indicate that math and science learning can be improved by spatial thinking [27,41]. Interventions that target spatial abilities can improve math performance and, at an early age, the intervention can have the shape of a game, as we will see in the next section.

4 Game-Based Learning to Improve Spatial and Numerical Cognition

Jirout and Newcombe [19] show that children's play with spatial toys (e.g., puzzles and blocks) correlates with spatial development. These authors underline that spatial skills can be improved, as they are malleable. It is possible to foster spatial skills in children as we teach them, as students' spatial skills are correlated with their success in learning science, both concurrently and predictively. This means that spatial skills can be trained also in early childhood, even before school entrance, also in home context [2]. In this study, the authors underline that, whereas language skills acquisition is supported at home by caregivers, math skills are stimulated in school context only. But, if a little help is given, for example, in the form of a mobile app, math skills improve. This means that together with a theoretical understanding on spatial and numerical cognition, it is relevant to design an educational approach which promotes spatial and numerical skills in the form of games. At the same time of training, these tools can be used for assessing spatial abilities [4,5] or related abilities such as reasoning [12] and soft-skills [22,29] also in children. Existing games that can be used for this goal are cards game and building blocks. Cards games not only implies counting and using symbolic representation of numbers, but also improve memory skills and strategic thinking. Building blocks is a game loved by children that stimulates spatial thinking [47,48].

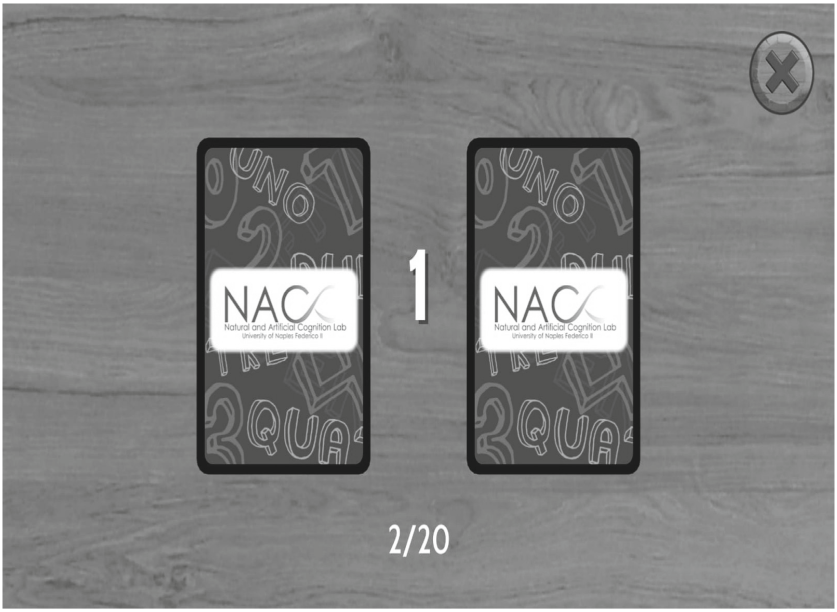

Fig. 1. A screenshot from Velocicards app in Android environment showing the moment before the cards are displayed

5 Examples of Technology Enhanced Version of Cards and Building Blocks

5.1 Velocicards: An Application to Strenghten Numerical Abilities

The first application we would like to introduce is the App Velocicards, an application that can be played on Android devices, shown in Fig. 1.

The games consists in selecting the card with the highest value between 2 cards. It records the speed of the selection on 20 attempts. The cards report the numbers from 0 to 9, represented in different codes, according to triple-code Dehaene model [7].

These codes are analogical (with dots or little characters) and symbolic (verbal and arabic numbers) and are pictured in Figs. 2 and 3.

The application allows to train people, including children, to shift quickly between the different codes, thus favouring the transition between analogic representation, connected with the natural endowment described above and the symbolic one, connected to formal education in maths. These cards represent a Technology-enhanced version of traditional card games where many statistics can be collected and which favours the involvement by children (see [10,33–37]).

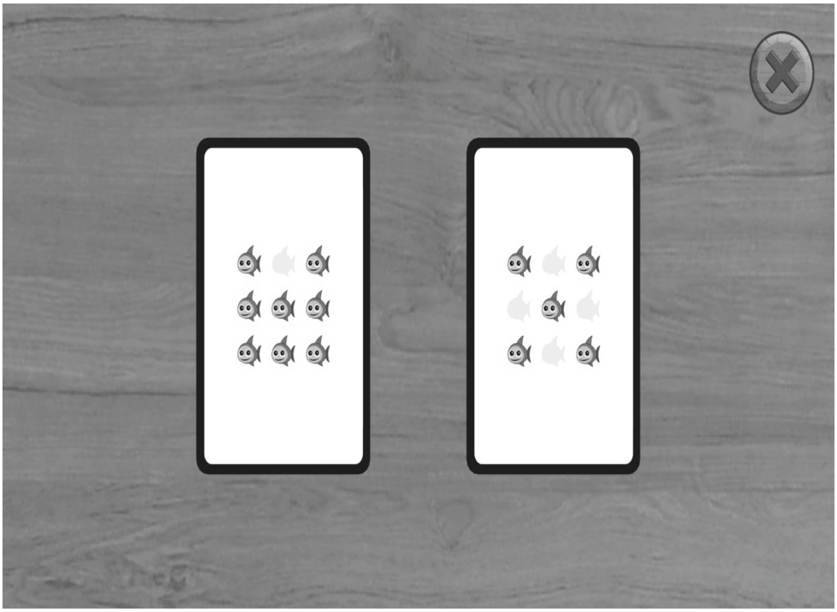

Fig. 2. An example of number analogic representation with little characters. The other one (not shown) is with black dots

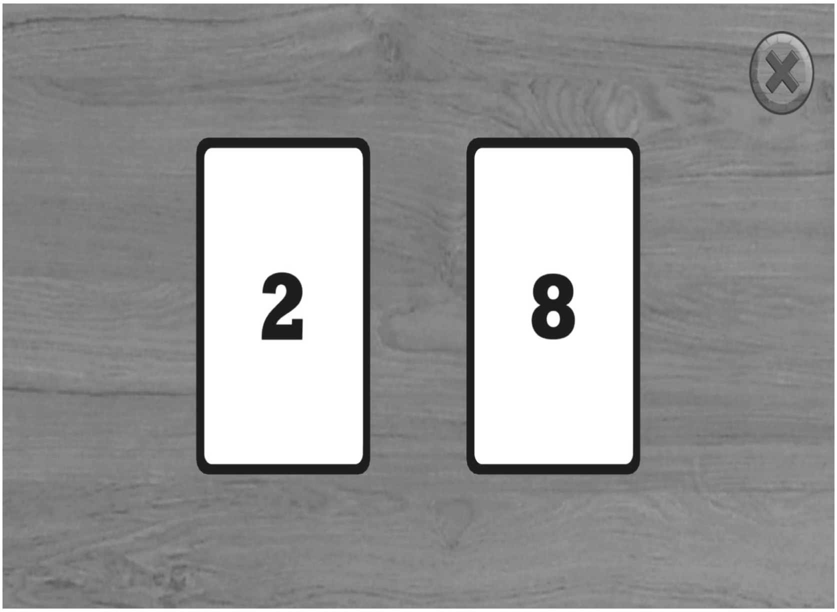

Fig. 3. An example of number symbolic representation with arabics. The other one (not shown) is with words

5.2 Flatlandia Creatures

Flatlandia creatures, whose name derives from the book "Flatland: A Romance of Many Dimensions" by Edwin Abbott are building blocks with different shapes and colours to build geometric features. These blocks are physical blocks that stimulate the embodied representation of space, but can be connected to a digital environment, creating a link between the physical and digital world which stimulates mental representation of spatial elements.

Also Flatlandia creatures represent a Technology-enhanced version of traditional building blocks that keep the advantage of the physical game, augmenting their educational possibilities thanks to technology.

6 Conclusions and Future Directions

Using cards and building blocks in their TEL version can be a very effective way to promote spatial and numerical skills. This is true for different reasons. The first one is related with the involvement that these tools have. In fact, today's children have the habit to play with digital materials and find them very attractive.

Moreover, using together physical and digital materials allows to exploit the embodied dimension augmented by the chance to record almost every aspect of children-game interaction. Embodied learning approaches underline that action can support educational objectives and also help the transition between analogic and symbolic dimension which is crucial in math learning. Another important aspect is related to the use of these tools in different context, included non-formal educational contexts such as home. In fact, whereas linguistic abilities are commonly strengthened informally by parents and caregivers, for example reading stories or with the daily linguistic interaction between children and adults, it is not so common that numerical skills are trained this way.

The next step will be to extensively test these tools with a longitudinal and experimental procedure that will follow groups of children at different ages to verify if the use of these tools can improve numerical abilities and later math school achievement, training spatial and numerical predispositions.

References

1. Ashcraft, M.H., Kirk, E.P.: The relationships among working memory, math anxiety, and performance. J. Exp. Psychol.: Gen. **130**(2), 224 (2001)
2. Berkowitz, T., et al.: Math at home adds up to achievement in school. Science **350**(6257), 196–198 (2015)
3. Butterworth, B.: What Counts: How Every Brain is Hardwired for Math (p. pp). The Free Press (1999)
4. Cerrato, A., Ponticorvo, M.: Enhancing neuropsychological testing with gamification and tangible interfaces: the baking tray task. In: Ferrández Vicente, J.M., Álvarez-Sánchez, J.R., de la Paz López, F., Toledo Moreo, J., Adeli, H. (eds.) IWINAC 2017. LNCS, vol. 10338, pp. 147–156. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-59773-7_16

5. Cerrato, A., Ponticorvo, M., Bartolomeo, P., Miglino, O.: Btt-Scan: Uno Strumento Per La Valutazione Della Negligenza Spaziale Unilaterale. SISTEMI INTELLIGENTI **2019**(1), Il Mulino (2019, in press)
6. Dehaene, S.: The Number Sense: How the Mind Creates Mathematics. OUP USA (2011)
7. Dehaene, S.: Varieties of numerical abilities. Cognition **44**(1–2), 1–42 (1992)
8. Dehaene, S.: The neural basis of the Weber-Fechner law: a logarithmic mental number line. Trends Cogn. Sci. **7**(4), 145–147 (2003)
9. Dehaene, S., Bossini, S., Giraux, P.: The mental representation of parity and number magnitude. J. Exp. Psychol.: Gen. **122**(3), 371 (1993)
10. Di Fuccio, R., Ponticorvo, M., Ferrara, F., Miglino, O.: Digital and multisensory storytelling: narration with smell, taste and touch. In: Verbert, K., Sharples, M., Klobučar, T. (eds.) EC-TEL 2016. LNCS, vol. 9891, pp. 509–512. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-45153-4_51
11. Doricchi, F., et al.: Spatial orienting biases in the decimal numeral system. Curr. Biol. **19**(8), 682–687 (2009)
12. Ferrara, F., Ponticorvo, M., Di Ferdinando, A., Miglino, O.: Tangible interfaces for cognitive assessment and training in children: LogicART. In: Uskov, V.L., Howlett, R.J., Jain, L.C. (eds.) Smart Education and e-Learning 2016. SIST, vol. 59, pp. 329–338. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-39690-3_29
13. Fischer, M.H., Shaki, S.: Spatial associations in numerical cognition-from single digits to arithmetic. Q. J. Exp. Psychol. **67**(8), 1461–1483 (2014)
14. Gilmore, C., Attridge, N., Inglis, M.: Measuring the approximate number system. Q. J. Exp. Psychol. **64**(11), 2099–2109 (2011)
15. Girelli, L., Lucangeli, D., Butterworth, B.: The development of automaticity in accessing number magnitude. J. Exp. Child Psychol. **76**(2), 104–122 (2000)
16. Halberda, J., Feigenson, L.: Developmental change in the acuity of the "number sense": the approximate number system in 3-, 4-, 5-, and 6-year-olds and adults. Dev. Psychol. **44**(5), 1457 (2008)
17. Hindman, A.H., Skibbe, L.E., Miller, A., Zimmerman, M.: Ecological contexts and early learning: contributions of child, family, and classroom factors during Head Start, to literacy and mathematics growth through first grade. Early Child. Res. Q. **25**(2), 235–250 (2010)
18. Huttenlocher, J., Newcombe, N., Sandberg, E.H.: The coding of spatial location in young children. Cogn. Psychol. **27**(2), 115–147 (1994)
19. Jirout, J.J., Newcombe, N.S.: Building blocks for developing spatial skills: evidence from a large, representative US sample. Psychol. Sci. **26**(3), 302–310 (2015)
20. Kaufman, E.L., Lord, M.W., Reese, T.W., Volkmann, J.: The discrimination of visual number. Am. J. Psychol. **62**(4), 498–525 (1949)
21. Lonigan, C.J.: Development, assessment, and promotion of preliteracy skills. Early Educ. Dev. **17**(1), 91–114 (2006)
22. Marocco, D., Pacella, D., Dell'Aquila, E., Di Ferdinando, A.: Grounding serious game design on scientific findings: the case of ENACT on soft skills training and assessment. In: Conole, G., Klobučar, T., Rensing, C., Konert, J., Lavoué, É. (eds.) EC-TEL 2015. LNCS, vol. 9307, pp. 441–446. Springer, Cham (2015). https://doi.org/10.1007/978-3-319-24258-3_37
23. Miglino, O., Ponticorvo, M., Bartolomeo, P.: Place cognition and active perception: a study with evolved robots. Connect. Sci. **21**(1), 3–14 (2009)
24. Miglino, O., Ponticorvo, M.: Place cognition as an example of situated cognition: a study with evolved agents. Cogn. Process. **10**(2), 250–252 (2009)

25. Möhring, W., Ramsook, K.A., Hirsh-Pasek, K., Golinkoff, R.M., Newcombe, N.S.: Where music meets space: children's sensitivity to pitch intervals is related to their mental spatial transformation skills. Cognition **151**, 1–5 (2016)
26. Newcombe, N.S.: Thinking spatially in the science classroom. Curr. Opin. Behav. Sci. **10**, 1–6 (2016)
27. Newcombe, N.S.: Picture this: increasing math and science learning by improving spatial thinking. Am. Educ. **34**(2), 29 (2010)
28. Newcombe, N.S., Huttenlocher, J.: Making Space: The Development of Spatial Representation and Reasoning. MIT Press, Cambridge (2003)
29. Pacella, D., Di Ferdinando, A., Dell Aquila, E., Marocco, D.: Online assessment of negotiation skills through 3D role play simulation (2015)
30. Ponticorvo, M., Rotondaro, F., Doricchi, F., Miglino, O.: A neural model of number interval position effect (NIPE) in children. In: Ferrández Vicente, J.M., Álvarez-Sánchez, J.R., de la Paz López, F., Toledo-Moreo, F.J., Adeli, H. (eds.) IWINAC 2015. LNCS, vol. 9107, pp. 9–18. Springer, Cham (2015). https://doi.org/10.1007/978-3-319-18914-7_2
31. Ponticorvo, M., Miglino, O.: Encoding geometric and non-geometric information: a study with evolved agents. Anim. Cogn. **13**(1), 157 (2010)
32. Ponticorvo, M., Gigliotta, O., Miglino, O.: Simulative models to understand numerical cognition. In: Ferrández Vicente, J.M., Álvarez-Sánchez, J.R., de la Paz López, F., Toledo Moreo, J., Adeli, H. (eds.) IWINAC 2017. LNCS, vol. 10337, pp. 75–84. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-59740-9_8
33. Ponticorvo, M., Di Ferdinando, A., Marocco, D., Miglino, O.: Bio-inspired computational algorithms in educational and serious games: some examples. In: Verbert, K., Sharples, M., Klobučar, T. (eds.) EC-TEL 2016. LNCS, vol. 9891, pp. 636–639. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-45153-4_80
34. Ponticorvo, M., Di Fuccio, R., Ferrara, F., Rega, A., Miglino, O.: Multisensory educational materials: five senses to learn. In: Di Mascio, T., et al. (eds.) MIS4TEL 2018. AISC, vol. 804, pp. 45–52. Springer, Cham (2019). https://doi.org/10.1007/978-3-319-98872-6_6
35. Ponticorvo, M., Rega, A., Miglino, O.: Toward tutoring systems inspired by applied behavioral analysis. In: Nkambou, R., Azevedo, R., Vassileva, J. (eds.) ITS 2018. LNCS, vol. 10858, pp. 160–169. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-91464-0_16
36. Ponticorvo, M., Rega, A., Di Ferdinando, A., Marocco, D., Miglino, O.: Approaches to embed bio-inspired computational algorithms in educational and serious games. In: CEUR Workshop Proceedings (2018)
37. Ponticorvo, M., Di Fuccio, R., Di Ferdinando, A., Miglino, O.: An agent-based modelling approach to build up educational digital games for kindergarten and primary schools. Expert Syst. **34**(4), e12196 (2017)
38. Romano, E., Babchishin, L., Pagani, L.S., Kohen, D.: School readiness and later achievement: replication and extension using a nationwide Canadian survey. Dev. Psychol. **46**(5), 995 (2010)
39. Rotondaro, F., et al.: The Number Interval Position Effect (NIPE) in the mental bisection of numerical intervals might reflect the influence of the decimal-number system on the Gaussian representations of numerosities: a combined developmental and computational-modeling study. Cortex (2018)
40. Shaul, S., Schwartz, M.: The role of the executive functions in school readiness among preschool-age children. Read. Writ. **27**(4), 749–768 (2014)

41. Sorby, S., Casey, B., Veurink, N., Dulaney, A.: The role of spatial training in improving spatial and calculus performance in engineering students. Learn. Individ. Differ. **26**, 20–29 (2013)
42. Snow, K.L.: Measuring school readiness: conceptual and practical considerations. Early Educ. Dev. **17**(1), 7–41 (2006)
43. Spelke, E.S.: Sex differences in intrinsic aptitude for mathematics and science?: A critical review. Am. Psychol. **60**(9), 950 (2005)
44. Spelke, E.S., Kinzler, K.D.: Core knowledge. Dev. Sci. **10**(1), 89–96 (2007)
45. Starr, A., Libertus, M.E., Brannon, E.M.: Number sense in infancy predicts mathematical abilities in childhood. Proc. Natl. Acad. Sci. **110**(45), 18116–18120 (2013)
46. Stevenson, H.W., Chen, C., Lee, S.Y.: Mathematics achievement of Chinese, Japanese, and American children: ten years later. Science, 53–58 (1993)
47. Verdine, B.N., Golinkoff, R.M., Hirsh-Pasek, K., Newcombe, N.S.: I. Spatial skills, their development, and their links to mathematics. Monogr. Soc. Res. Child Dev. **82**(1), 7–30 (2017)
48. Verdine, B.N., Golinkoff, R.M., Hirsh-Pasek, K., Newcombe, N.S., Filipowicz, A.T., Chang, A.: Deconstructing building blocks: preschoolers' spatial assembly performance relates to early mathematical skills. Child Dev. **85**(3), 1062–1076 (2014)
49. Wood, G., Willmes, K., Nuerk, H.-C., Fischer, M.: On the cognitive link between space and number: a meta-analysis of the SNARC effect. Psychol. Sci. Q. **50**(4), 489–525 (2008)