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PLAYING READING, USING HANDS: WHICH ACTIVITIES ARE LINKED TO NUMBER-SPACE PROCESSING IN PRESCHOOL CHILDREN?

Literate subjects from Western cultures form spatial-numerical associations (SNA) in left-to-right direction, which follows their reading habits. In preliterate children, sources of SNA directionality are more disputable. One possibility is that SNA follows children's early knowledge about text orientation. It could also reflect ipsilateral/contralateral tendencies in manual task execution. Furthermore, SNA's characteristics could differ depending on the evaluation method used. In this study, we test SNA in preliterate preschoolers using object counting, finger counting, and numerosity arrangement tasks. We examined the relations of SNA to children's directional reading knowledge and their manual response tendencies. Left-to-right SNA was pronounced for object counting, disappeared for the numerosity task, and was reversed for finger counting. In all tasks, left-to-right SNA dominated in children who responded contralaterally with their hand. Reading knowledge was partially related to numerosity-based SNA, but not to other SNAs. Based on these findings, we discuss developmental characteristics of different forms of number-space associations.

Key words:counting, spatial-numerical associations, reading knowledge, numerosity

Introduction

Spatial processing is closely related to a wide range of perceptual-motor actions and seemingly abstract forms of conceptual thinking (for reviews see Chokron, Kazandjian, & De Agostini, 2009; Kazandjian & Chokron, 2008). Linguistic – cultural factors also shape the spatial properties of perceptual-motor

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action. One of the most compelling demonstrations of such a relationship can be found in the domain of number cognition: When adult participants judge the parity or magnitude of relatively small numbers they are faster to respond on the left side (e.g. with the left-located button), and when they judge parity or magnitude of large numbers they are faster to respond on the right side. This effect, called SNARC (Spatial-Numerical Associations of Response Codes, Dehaene, Bossini, & Giraux, 1993), is considered as the most prominent effect that shows that number processing can be oriented in space (for reviews see Fischer & Shaki, 2014; Gevers & Lammertyn, 2005; Wood, Willmes, Nuerk, & Fischer, 2008). A particular orientation of SNARC is mostly attributed to the direction of language orthography in a given culture: Whereas the left-to-right/small-to-large association is usually observed in left-to-right reading societies (Western countries), this association reverses or disappears in right-to-left reading cultures (Middle-Eastern countries, Dehaene, Bossini, & Giraux, 1993; Rashidi-Ranjbar, Goudarzvand, Jahangiri, Brugger, & Loetscher, 2014; Shaki & Fischer, 2008; Shaki, Fischer, & Petrusic, 2009; Zebian, 2005).

Number-space associations are examined not only in adults but also in other age groups including school pupils (Berch, Foley, Hill, & Ryan, 1999; Imbo, Brauwer, Fias, & Gevers, 2012; van Galen & Reitsma, 2008) and even preschool children (for reviews see de Hevia, Girelli, & Cassia, 2012; McCrink & Opfer, 2014; Patro, Nuerk, Cress, & Haman, 2014). The appearance of a number-space link in this second group might be at first glance surprising, given that children who are before formal school education cannot yet read and write properly. So, the direction of SNA in these children cannot be explained simply by their reading experience. This might indicate that other experiences or skills might be crucial for establishing the direction of number-space mapping in this early period of life.

However, one disputable issue is whether the direction in which children map numbers to space always reflects the same underlying representation or rather various forms that might differ in their basic properties and origins. This might be a valid question given that the measures used to assess SNA in preschoolers differ substantially from those used with adults (which are usually based on speeded parity/magnitude judgment of Arabic numbers). For instance, one popular task to study SNA in preschoolers is object counting, in which children are asked to count tokens arranged in a horizontal row (Shaki, Fischer, & Göbel, 2012). Some researchers also analyze the direction in which children count with their fingers (Knudsen, Fischer, & Aschersleben, 2015; Rinaldi, Gallucci, & Girelli, 2016) or the speed of spatial responses to non-symbolic numerosities (Patro & Haman, 2012; Ebersbach, Luwel, & Verschaffel, 2014). Although all these tasks evaluate number-space interactions to a certain extent, they might in fact rely on different aspects of space and number processing. If this is the case, one could expect that different kinds of SNA develop based on different mechanisms, so they might also be related to different skills or experiences.

Taking all these issues into account, we will examine in the present study how different forms of number-space associations emerge in preschool children, and how each of these forms is related to certain cultural and bodily factors that appear to be important in early preschool age: knowledge about reading conventions and ipsi-/contralateral manual response patterns.

Multiple number-space associations in preschool children

Among the various SNA operationalizations described in the literature (for reviews and taxonomies see Patro et al., 2014; Cipora, Patro, & Nuerk, 2015), at least three are commonly used in studies with preschool children.

First, preschool children may form associations between spatial directions and numerical cardinalities, i.e. magnitudes represented by a numerical stimulus. This type of SNA is usually observed as SNARC-*like effects*, which are based on spatially oriented responses to smaller and larger numerical magnitudes, and are analogous to SNARC effects reported in adults. In the studies performed so far, left-to-right SNARC-like effects have been revealed in preschool children with the symbolic format of Arabic numbers (Hoffmann, Hornung, Martin, & Schiltz, 2013; Yang et al., 2014), spoken numerals (Nava, Rinaldi, Bulf, & Macchi Cassia, 2017), as well as non-symbolic format of sets' numerosities (Ebersbach et al., 2014; Patro & Haman, 2012). This last numerical format appears to be of particular importance for developmental studies on SNA, since processing of numerosities does not require any formal numerical knowledge (e.g. Xu, Spelke, & Goddard, 2005). Thus, the non-symbolic SNARC, in contrast to the symbolic SNARC, can be tested in children as young as 3 and 4 years (Patro & Haman, 2012) and even in 7-months-old infants (Bulf, de Hevia, & Macchi Cassia, 2016; de Hevia, Girelli, Addabbo, & Macchi Cassia, 2014).

Preschoolers can also create a spatial-numerical link while counting a series of objects. By starting from one side of a row and moving towards the other side, they form a link between a unique spatial position (e.g. leftmost, rightmost) and an ordinal numerical position (1^{st}, 2^{nd},…). This mapping usually proceeds from left to right in Western cultures, similarly to SNARC-like effects (Opfer & Furlong, 2011; Opfer & Thompson, 2006; Opfer et al., 2010; Shaki et al., 2012). However, in contrast to this first category of SNA, the ordinal counting-based SNA already requires some basic numerical knowledge: A child should know at least a few numerals from a counting list, and also certain counting rules like one-to-one correspondence between objects and number words (Gelman & Gallistel, 1978). Furthermore, the spatial association is formed not for magnitudes (cardinalities) but for numerical ordinalities. One valid but thus far unresolved question is whether such ordinal spatial mapping is nevertheless enhanced by acquisition of the cardinal counting principle, i.e. knowing that the last spoken numeral represents the numerosity of a counted set (Le Corre

& Carey, 2007; Wynn, 1992; for discussion on the relation between this principle and the ability to order numerals along physical line see Sella, Berteletti, Lucangeli, & Zorzi, 2017).

Another way to operationalize number-space associations is to focus on the way children count with their fingers, i.e. the way they assign ordinal numerals to corresponding positions on their hands. Although *finger counting* is a special case of a counting activity, this kind of SNA measure differs in at least two important aspects from the above-described object counting task. First, whereas in object counting numerals are mapped onto external space, in finger counting they are mapped directly onto body parts (fingers). In this sense, finger counting is often assumed as an index of embodied number-space representation (Fischer, 2008; Fischer & Brugger, 2011; Lindemann, Alipour, & Fischer, 2011). Second, the direction of finger counting is less homogenous and less consistent with the commonly observed left-to-right spatial pattern revealed in other numerical tasks (for review and discussion see Previtali, Rinaldi, & Girelli, 2011; Bender & Beller, 2012). In fact, most studies conducted in Western societies point to the right-to-left preference (starting from the right thumb) as a dominant pattern among preschoolers (Knudsen et al., 2015; Newman & Soylu, 2014; Rinaldi, Gallucci, & Girelli, 2016; Sato & Lalain, 2008). This spatial pattern seems to prevail even in older children and adults (Knudsen et al., 2015; Wasner, Moeller, Fischer, & Nuerk, 2014), although it can be modulated by specific task settings (e.g. filling out a questionnaire, Fischer, 2008; Lindemann et al., 2011) and vary between different populations (e.g. left-handers, Previtali, & Girelli, 2009; blind subjects, Crollen, Mahe, Collignon, & Seron, 2011).

To summarize, spatial-magnitude mapping, object counting, and finger counting are commonly used to test SNA in preschool children. However, each of these measures seems to refer to a different aspect of number-space processing: i.e. mapping of cardinal numbers onto external (extrapersonal) space, mapping of ordinal numbers onto external (extrapersonal) space, and mapping of ordinal numbers onto internal (peripersonal, embodied) space. This might lead to the question of whether development of number-space associations can be viewed as one unitary process or, rather, there are different types of number-space representations that develop separately, and are associated with different skills and experiences.

How knowledge about reading conventions may be related to number-space associations in preliterate children

Experience with reading and writing is regarded as one of the main factors shaping number-space associations in adults and school-aged children (Dehaene et al., 1993). Two recent cross-cultural studies suggest that preliterate children can already form number-space links consistently with reading habits dominant in their society. This has been demonstrated at least for the direction of object counting. In one study, Arabic- and Hebrew-speaking preschoolers counted tokens from right to left, in contrast to their English-speaking peers who counted tokens from left to right (Shaki et al., 2012). Another study revealed a similar relation with reading direction for vertical counting: whereas most English-speaking children counted tokens from top to bottom, Chinese children counted them from bottom to top (Göbel, 2015). How could one explain this reading-consistent direction of counting in preliterate children?

One possibility is to assume that reading and writing skills do not have to be explicit to affect the direction of number processing. Three and four-year-old children might learn about reading-specific direction by observing how their parents or caregivers read books to them (for early engagement of children in joint reading activity see Fletcher & Reese, 2005; Sénéchal, Cornell, & Broda, 1995). Children from left-to-right reading societies could observe that adults point with their finger or turn their head to the left side of a text line (or to the left page) when they start reading, and to the right side when they finish reading. Children from right-to-left reading societies could be exposed to an opposite reading behavior of adults. This proposal is consistent with a recent observation of Göbel, Fischer and Shaki (2014), who showed that English-speaking children were more likely to count from the left and Arab children from the right, if they observed just beforehand how parents had read books to them in their native language. Apparently, implicit reading instructions that children receive from their parents might exert some influence on their counting direction, at least immediately after joint book reading activity.

However, it is not clear from the above studies whether preschoolers indeed consolidate the knowledge about reading pattern via joint book reading (i.e. whether they know where the story should start and where it should end), or if they just extract more general spatial cues from the reading behavior of their parents (e.g. head turning pattern, finger movement) but do not associate these cues with cultural script conventions. As has been recently shown by McCrink and colleagues (2017), parents also spontaneously use culture-consistent directional gestures while interacting with their children in a non-reading context. For instance, while watching pictures together or telling stories, they point to or order pictures in a direction consistent with their reading habits. Thus, reading-related spatial cues might also be transmitted to preschoolers in such an indirect way, even before children understand the spatial structure of a written text.

Another question is whether potential knowledge about script conventions could be related to number-space processing in general, or whether this relation could just be specific to the direction of object counting. On the one hand, not only reading direction but also SNARC-like effects emerge from left to right in preschoolers raised in Western societies (Ebersbach et al., 2014; Hoffmann et al., 2013; Patro & Haman, 2012), which might suggest some association to reading knowledge. On the other hand, there are reasons to suppose that implicit reading preferences more easily affect the object-counting SNA than other forms of associations. Because both reading and counting are typical cultural activities, children may expect that these activities should follow similar directional procedures (i.e. starting from one side, finishing on the other side). Moreover, reading and counting have a very similar spatial structure, namely, both are organized along the horizontal plane and engage a similar movement pattern: children point with a finger to consecutive words while learning to read, as they also do while counting tokens. In contrast, comparison of numerosities (SNARC-like tasks) relies mostly on selecting one numerosity (*Where are more objects?*) or one response side (*Press the left button if there are more objects*), and not on consistent left-to-right movement. Thus, the bond between children's reading preferences and numerosity-based SNA seems to be less direct. Finally, as suggested by some studies with children and adults (e.g. Knudsen et al., 2015; Rinaldi, Di Luca, Henik, & Girelli, 2016; Wasner et al., 2014), the direction of finger counting might be linked to a larger extent to body-related factors, like handedness, than to cultural reading conventions. On the other side, there is much diversity in the way numbers are encoded by fingers in different cultural societies (Bender & Beller, 2012). Therefore, biological factors may also interact to some extent with cultural reading-related factors in establishing the specific direction of a finger counting pattern (Previtali et al., 2011; Lindemann et al., 2011).

How manual response pattern may be related to number-space associations in preliterate children

Implicit reading knowledge could be one but not the only factor associated with SNA direction in preschool children. Clearly, SNAs are not always formed consistently with cultural habits, especially not in preschool age. For instance, SNA can be oriented from right to left in a spontaneous finger counting task even in subjects from Western countries (Knudsen et al., 2015; Wasner et al., 2014). Also, the direction of object counting of preschoolers is not as culture-consistent as in adults because many children still prefer to count from right to left (e.g. as reported by Shaki et al., 2012, 39.3% of preschoolers and only 9% of adults from Western cultures counted from the right). Lately, Patro, Nuerk and Cress (2015) examined the role of a counting hand in exerting spatial biases in the object counting task. They found that children who were asked to count with the left hand were more likely to count from the left side, as compared to children who were asked to count with the right hand. A similar association between hand and directionality was found for adding and subtracting objects to or from a row (van't Noordente, Volman, Leseman, & Kroesbergen, in press). Therefore, we assume that spatial-numerical biases in children are not only linked to culture-specific factors, such as reading knowledge, but they might also rely on body-related factors, such as a responding hand.

In tasks like reaching or pointing, preschool children usually exhibit the effect of midline crossing inhibition (MCI): they prefer to reach for or place an object on the side ipsilateral to the used hand, or to do so with the hand ipsilateral to the side of a planned action (Bradshaw, Spataro, Harris, Nettleton, & Bradshaw, 1988; Carlier, Doyen & Lamard, 2006; Gabbard, Helbig, & Gentry, 2001; Gleissner, Bekkering, & Meltzoff, 2000; Hausmann, Waldie, & Corballis, 2003; Leconte & Fagard, 2006; Screws, Eason, & Surburg, 1998; van Hof, van der Kamp, & Savelsbergh, 2002). This effect is age-specific and disappears in older children (Cermak, Quintero, & Cohen, 1980). Because the assessment of spatial and numerical knowledge is mostly based on manual tasks (which require that children respond with a hand in left or right hemispace), we suppose that spatial-numerical biases in preschoolers might be related to a certain response pattern - ipsilateral or contralateral - which occurs in their performance.

Analogously to our predictions regarding the relation between reading knowledge and the number-space link, we expect that the importance of a certain response pattern for SNA may also be diversified. So far, the hand side was shown to influence the direction of object counting (Patro et al., 2015). Because many preschool children spontaneously choose the right hand for counting (e.g. due to developing right-handedness, Gudmundsson, 1993) they might prefer to start counting from the right side, even if this pattern is opposite to the spatial conventions in their society. This could be a matter of functional ergonomics, which allows for clear visibility of to-be-counted items, and which could overcome cultural directional habits that are not yet well developed. The hand preference could be even more strongly linked to the direction of SNA assessed with the finger counting task because numbers are mapped in this task directly onto fingers - an inherent part of the hand. Thus, any directional biases revealed in this sort of SNA could be a simple consequence of the fact that finger counting habits are embodied. In the case of cardinal (magnitude-based) SNA, we suppose that ipsilateral tendencies would reduce any number-space biases. This might happen because responding ipsilaterally to both small and large magnitudes could result in a general right-sided (or left-sided) bias instead of a number-specific spatial bias.

Objectives of the present study

Starting with the assumption that different SNA assessments may refer to different aspects of number-space processing, we examine in the present study how those different SNA effects develop in preschool children. In particular, we are interested in whether and how early acquired knowledge about reading direction (cultural-linguistic factor) and manual response pattern (ipsi- vs. contralateral) (body-related factor) are associated with each type of SNA: the direction of object counting (ordinal SNA with reference to physical space), direction of finger counting (ordinal SNA with reference to bodily space), and a side preference for numerosities (cardinal SNA based on non-symbolic number processing). Potential similarities or differences between the relations of those factors and the three forms of SNA would allow for concluding whether those number-space associations develop together or rather separately.

Material and methods

Participants

Fifty-seven children (25 girls, 32 boys; mean age: 4.1 years, age range: 3.3-5.2 years) were tested. Thirty-one children (54%) were below or at the age of 4 years, and 26 children (46%) were above this age. All of them were recruited from preschools located in an urban area in Poland. Three more children were also tested, but they were excluded because their responses in a reading task could not be recorded (2 children did not complete the task and 1 child did not follow the instructions). Written informed consent was obtained from all parents or caregivers of the children.

Tasks and procedure

Each child was tested individually, in a separate quiet room located in their preschool building. During testing, the experimenter and the child were sitting at a table, opposite to each other. In all the tasks, the experimenter put materials on the table, centrally in front of the child. The procedure was recorded with a camcorder, which was placed out of the child's sight. A research assistant, who was also sitting out of the child's sight, recorded children's responses by writing them down into a response form.

The whole experiment was divided into two sessions. Each of the session consisted of four tasks presented to all children in the same order. Spatial preferences for text organization were tested with the *Pretended reading* task. Two forms of the ordinal number-space associations were tested with the *Object counting* task and with the *Finger counting* task. The cardinal SNA (SNARC-like effect) was tested with four trials of the *Numerosity* task. In this task, we used more than one trial because SNARC-like tasks are based on comparison of relative spatial responses to smaller and larger numbers (which requires at least two trials). In addition to these measures, we used the *Give-a-number* task to test whether the children had acquired the cardinal principle of counting (which allows for mapping between number words and distinct numbers of elements). This controlled for potential developmental changes in number-space associations triggered by acquisition of the verbal numerical system (cf. Knudsen et al., in press; Patro & Haman, 2012; Patro et al., 2014 for potential relation between SNAs and cardinal principle knowledge).

In the first session, children performed the following tasks: *Numerosity* task (1st trial), *Give-a-number* task, *Pretended reading* task, *Numerosity* task (2nd trial), and in the second session: *Numerosity* task (3rd trial), *Finger counting*, *Object counting*, *Numerosity task* (4th trial). These tasks were always presented in the same order, as listed above. This specific order allowed for minimizing potential influences of reading and counting behavior on the numerosity task, which was always presented at the beginning and end of each session. It also prevented mutual influences between spatial biases in reading and counting.

The order of the sessions was also kept constant for all the children. There was a break between the sessions, which lasted about one hour.

In the *Numerosity* task (evaluating cardinal SNA), the experimenter showed the child a sheet of paper (A4) with two identical buckets (white with black borders, 10 x 8 cm) drawn against a white background. The buckets were placed symmetrically to each other, one on the left and one on the right side of the page. Above the sheet, the experimenter placed two circles (diameter: 5.4 cm) cut out of thick paper, with one circle under the other. Within each circle there were 2, 4, 8 or 16 randomly distributed colored rectangles. The circles were matched in pairs to represent either a small number range - with 2 and 4 elements - or a large number range - with 8 and 16 elements. Thus, numerosities were always matched in the proportion 1:2, which is usually easy to discriminate for preschool children (Halberda & Feigenson, 2008). The total surface of all rectangles within each circle was always the same and equal to 647.5 mm^2 (to reduce potential confound resulting from positive correlation between total surface and number of objects, cf. Patro & Haman, 2012). In the beginning of the task, the experimenter said: *Look, here are two buckets, and here are some cards with building blocks. Could you, please, choose a card with more (fewer) blocks on it and put it into one bucket? Remember, there must be more (fewer) blocks on a card*. If the child chose a wrong card, the experimenter explained that the card contained fewer (more) blocks and asked for more (fewer) blocks. In such a situation, a child was allowed to repeat the trial. If the repeated trial was still wrong, the experimenter moved to another task. The research assistant recorded into which bucket (left vs. right) the child put the card with a given number of objects. The hand with which the child performed the task was also recorded.

This task was repeated three more times: once at the end of the first session, and once at the beginning and end of the second session. The instruction (*Choose more blocks* vs. *Choose fewer blocks*) and number range (2-4 vs. 8-16) varied systematically within each subject, following the Latin square design (ABBA). The relative vertical position of two cards (more on the top, fewer on the bottom vs. fewer on the top, more on the bottom) differed within each subject between two sessions (AABB). The order in which instructions, number ranges, and positions of the cards changed from trial to trial was counterbalanced across participants.

In the *Give-a-number* task (which assessed knowledge of the cardinal counting principle), the experimenter introduced a plush duck to a child by saying: *Look! This is Tekla. She would like to play with you. She is hungry today. Could you feed her?* When the child agreeded, the experimenter placed 11 wooden carrots in front of the child. Then, the duck came to the child and said: *Oh! Carrots! I like them so much! Could you give me one carrot, please?* When the child gave the correct number of carrots, the duck asked for X+2 objects. When the child gave an incorrect number, the duck asked for X-1 objects. The procedure was repeated until the child succeeded with 9 objects, or he/she succeeded two times with X objects, but failed two times with X+1 objects. The experimenter's assistant recorded the highest number with which the child succeeded. Children who succeeded with numbers higher than 4 were assigned to the CP-knowers (Cardinal-Principle-knowers) group, and the other children to the non-CP-knowers group (cf. Le Corre & Carey, 2007; Patro & Haman, 2012 for a similar criterion).

In the *Pretended reading* task (which assessed knowledge of reading direction), the experimenter put a white sheet of paper (A5 format) on a table, centrally in front of the child, with 6 lines of a children's poem. The poem was printed in black font of 20 pt. size. All lines were aligned centrally on a page and justified (each line was 14.7 cm long). The experimenter instructed the child: *Look, this is a poem. Could you please show me with your finger where this poem starts? Then, I will read it to you.* After the child pointed to some place on the page, the experimenter started reading. When she stopped reading, she asked: *Could you please show me now with your finger where this poem stops?* The assistant recorded the line indicated by the child each time, and whether the child pointed to its beginning (represented by the first word), its end (represented by the last word), or to some other place in between.

In the *Finger counting* task (assessing ordinal SNA), the experimenter first asked the child to imitate her movements: interlacing fingers, clapping hands and then putting both hands on the lap, to make sure that the hands were in the same position before the main task started. When the child made all these movements, the experimenter said: *Could you please count with your fingers of both hands up to 10?* If the child did not start counting or said that she/he could not do it, the experimenter offered to count aloud while the child would straighten his/her fingers to imitate counting. The assistant recorded the hand from which the child started counting, how each hand was positioned during counting (palm up vs. down), and how the spoken number words were mapped onto the fingers.

Finally, in the Object counting task (assessing another form of ordinal SNA) children were asked to count four flowers (4 x 4 cm) presented on an A4 white sheet of paper. The flowers were aligned in a horizontal row and distributed symmetrically with respect to the vertical midline of the page. The distance between neighboring objects was always the same and equal to 2 cm. The experimenter placed the sheet centrally in front of the child and said: *Look, here we have flowers. Could you count these flowers and tell me how many of them are here?* If the child started counting without pointing to each object with a finger, the experimenter said: *Could you count with your finger?* If the child refused to count alone, the experimenter encouraged the child by saying: *Let's count together! I will now count aloud and you will point to each flower with your finger*. The assistant recoded the direction of counting and the hand used by the child.

Results

Preliminary analyses: Reading knowledge

Only five children (9%) indicated correctly that the poem started on the left side of the upper line, and ended on the right side of the bottom line. For further analyses, children's responses were coded as located along the horizontal plane - all responses made at the beginning of the text line (represented by the first word) or at the end of the text line (represented by the last word) were coded as "left" or "right", respectively. Responses made by pointing to other places on a text line were coded as "middle."

First, we categorized the children's responses according to the indicated spatial location of the beginning and end of the text (categories: "left", "right", "middle"). As regards the text beginning, the frequencies were approximately the same in the entire group: 22 children (39%) located the starting point of the text on the left side, 16 children (28%) on the right side, and 19 children (33%) in the middle of the text line, $\chi^2(2) = .947$, $p = .623$. Children with a left-starting preference were older (median = 4.5 years) than children with right- (median = 3.8 years) and middle-starting preferences (median = 3.9 years) (*ps* < .005, Mann-Whitney U tests). As regards the endpoint of the text, most of the children (25 children, 44%) located it in the middle of the line, whereas 10 children (18%) located it on the left side and 22 children (39%) on the right side, $\chi^2(2) = 6.632$, $p = .036$. So, the frequencies of answers consistent with cultural conventions (start on the left, end on the right) were rather low, and did not differ between the two instruction conditions (pointing to the beginning vs. pointing to the end; McNemar test, $p = 1.0$).

To have a closer look at the children's directional responses in this task, we analyzed in the next step whether the endpoint of the text was indicated by the child as located to the right from the beginning of the text (left-to-right text orientation), to the left (right-to-left text orientation), or in the same position (no orientation along horizontal plane). According to this score, most of the children (31 children, 54%) revealed no directional response pattern, 18 children (32%) indicated the text to be oriented from left to right, and 8 children (14%) from right to left, $\chi^2(2) = 14.000$, $p = .001$ (the relative advantage of left-to-right over right-to-left pattern did not reach significance, binomial test, $p = .076$). Again, children responding consistently with the left-to-right direction were slightly older (median = 4.4 years) than children responding consistently with the right-to-left direction (median 3.6 years) and those showing no directional preferences (median 4.0 years) (*ps* < .09, Mann-Whitney U tests).

See Table 1 for detailed data of the children's spatial responses in the *Pretended reading* task.

Table 1. Main patterns of spatial reading knowledge and their frequencies among children

Indicated direction of text	Number of children (%)
Left-to-right patterns	
Left-Right	*N* = 5 (9%)
Left-Middle	*N* = 3 (5%)
Middle-Right	*N* = 2 (3%)
	Σ = 10 (17%)
Right-to-left patterns	
Right-Left	*N* = 3 (5%)
Right-Middle	*N* = 3 (5%)
Middle-Left	*N* = 2 (3%)
	Σ = 8 (13%)
Non-directional patterns	
Left-Left	*N* = 6 (10%)
Right-Right	*N* = 12 (21%)
Middle-Middle	*N* = 14 (24%)
	Σ = 32 (55%)

Main analyses: Spatial-numerical associations

In this section, we examine the characteristics of different forms of number-space associations (*Object counting*, *Finger counting*, *Numerosity* task) by analyzing (i) the appearance and direction of a respective form of SNA, (ii) its relation to reading knowledge, and (iii) its relation to manual response pattern (ipsilateral, contralateral).

For some children, not all responses could be entered into analyses. Some children made errors in the *Numerosity* task (they selected wrong cards), and others did not count with their fingers in a standard continuous way (one by one). We excluded those children separately for each of the spatial-numerical tasks. Therefore, the total number of participants included for further analyses differed between all three tasks.

Object counting (*ordinal SNA*): All 57 children were included in the analyses. All of them started counting from the outermost element and maintained an unequivocal counting direction: Thirty-seven children (65%) counted from left to right, and 20 children (35%) counted from right to left (binomial test, $p = .033$), which suggests the emergence of spatial-numerical association. No relation was found between the direction of counting and the cardinality principle knowledge, Fisher's exact test, $p = 1.0$ (left-to-right counting was observed in 20 out of 31 CP-knowers and in 15 out of 22 non-CP knowers[1]). Children counting from left to right did not differ in age from children counting from right to left, $U = 318.0$, $p = .39$.

The left-to-right counting pattern was prevalent in all “reading” groups, including those groups defined by the direction for text organization (Fisher-Freeman-Halton exact test, $p = .37$), and those defined by the location of the text beginning (Fisher-Freeman-Halton, $p = .32$). However, the counting direction differed between children who used their left or right hand to perform the task, Fisher’s exact test, $p < .001$. Most of the children (39 children, 68%) started counting from the side that corresponded to the used hand (19 children from the left side, and 20 children from the right side). The remaining 18 children (32%) counted from left to right with the right hand. Not a single child counted from right to left with the left hand. Thus, the midline crossing always triggered a culture-consistent, left-to-right counting pattern. The results for this task are summarized in Table 2.

Table 2. Frequencies and percentages of children who counted objects from left-to-right or right-to-left, in relation to their reading knowledge (referring to text orientation and location of text beginning), and to manual response pattern

Object counting (N = 57)				
Counting direction			**Left-to-right**	**Right-to-left**
Total			37 (65%)	20 (35%)
Reading knowledge	Text orientation	Left-to-right	12 (21.1%)	6 (10.1%)
		Right-to-left	7 (12.3%)	1 (1.8%)
		No direction	18 (31.2%)	13 (22.8%)
	Text beginning	Left	17 (29.8%)	5 (8.8%)
		Right	9 (15.8%)	7 (12.3%)
		Middle	11 (19.3%)	8 (14.0%)
Manual response pattern		Ipsilateral	19 (33.3%)	20 (35.1%)
		Contralateral	18 (31.6%)	0 (0%)

Finger counting (*ordinal SNA*): To code the direction of finger counting, we took into account two aspects: first the palm orientation (i.e. whether the palm was oriented up/towards the body or down/away from the body) and then the finger from which the child started counting. For instance, if the child started counting with the right thumb, the direction of counting was coded as left-to-right when his/her palm was oriented downwards, but as right-to-left when the palm was oriented upwards. With such a coding applied, most of

[1] Due to experimenter’s error in the *Give-a-number* task, the level of cardinal knowledge was not recoded for four children. Therefore, the analyses including cardinal knowledge as a variable are made for respectively smaller group of children.

the children (45 children, 79%) exhibited an anatomical symmetry while counting: the direction of counting with the first hand was mostly opposite to the direction of counting with the second hand (for a similar pattern in adults see Lindemann et al., 2011). Therefore, we restricted our analyses to the directional counting pattern observed for the first hand only. We excluded five children for whom the counting direction (registered for the first hand) could not be coded as left-to-right or right-to-left. Altogether, the final group for the subsequent analyses was comprised of 52 children. Most of the children from this group (43 children, 83%) counted with the palm facing up/towards the body.

We observed a different overall directional pattern for this task than for the object counting task. Thirty-five children (67%) raised their fingers in a right-to-left fashion, and only 17 children (33%) in a left-to-right fashion (binomial test, p = .018). This directional preference was not related to cardinality knowledge, Fisher's exact test, p = .36 (right-to-left counting was observed in 21 out of 29 CP-knowers, and in 11 out of 19 non-CP knowers). No age difference was observed between left-to-right and right-to-left counting children, U = 222.5, p = .15.

As regards the hypothesized relation between counting direction and reading knowledge, no significant result was obtained (counting direction by text orientation, Fisher-Freeman-Halton, p = .84; counting direction by text beginning, Fisher-Freeman-Halton, p = .81). More children counted in a right-to-left fashion in all of the groups. However, the counting direction was strongly related to the starting hand, Fisher's exact test, p < .001. Forty-five children (87%) counted in the direction corresponding to the used hand (12 children from left to right and 33 children from right to left) and only seven children (13%) counted contralaterally (five children from left to right with the right hand and two children from right to left with the left hand). The results for this task are summarized in Table 3.

Numerosity task (cardinal SNA): Eleven children were excluded from the analyses of this task because they made a mistake in more than one trial (which means accuracy equal to or lower than 50%); these children selected either a wrong card (i.e. a card containing fewer elements instead of more elements, or vice versa) or two cards instead of one. After excluding these children, the final group consisted of 46 subjects.

To evaluate the size and direction of SNA in this task, we computed a proportion of trials for each child in which responses were consistent with left-to-right spatial-numerical mapping (i.e. smaller numerosities placed on the left side, and larger numerosities on the right side). Proportions higher than .50 indicated dominance of left-to-right number-space mapping, proportions lower than .50 indicated dominance of right-to-left mapping, and proportions equal to .50 indicated no dominant mapping. For further analyses, we transformed the proportion assigned to each child with an arcsine function to approximate a normal distribution. Because for some children (n = 40) the proportional score was computed from four trials and for other children (*n* = 6) from three trials, we assigned weights to each observation: proportions computed from 4 trials had a weight equal to 1, and proportions computed from 3 trials had a weight equal to 0.75.

Table 3. Frequencies and percentages of children who counted with their fingers from left-to-right or right-to-left, in relation to reading knowledge (referring to text orientation and location of text beginning), and to manual response pattern.

Finger counting (N=52)				
Counting direction			**Left-to-right**	**Right-to-left**
Total			17 (33%)	35 (67%)
Reading knowledge	Text orientation	Left-to-right	5 (9.6%)	12 (23.1%)
		Right-to-left	3 (5.8%)	4 (7.7%)
		No direction	9 (17.3%)	19 (36.5%)
	Text beginning	Left	6 (11.5%)	16 (30.8%)
		Right	5 (9.6%)	9 (17.3%)
		Middle	6 (11.5%)	10 (19.2%)
Manual response pattern		Ipsilateral	12 (23.1%)	33 (63.5%)
		Contralateral	5 (9.6%)	2 (3.8%)

Initial inspection of the data showed no prevailing spatial-numerical pattern at a group level, $t(45) = -0.045$, $p = .97$, $\text{mean}_{\text{not transformed}} = 0.49$[2]. Seventeen children (37%) assigned relative numerosities to SNA-congruent spatial locations equally often as to SNA-incongruent spatial locations (raw SNA score = .50). The rest of the children (63%) exhibited either an advantage for the left-to-right/smaller-to-larger mapping (raw SNA score > .50, 14 children, 30%) or for the right-to-left/smaller-to-larger mapping (raw SNA score < .50, 15 children, 33%), with no overall prevalence of any of these patterns. The SNA score was only slightly higher in the group of non-CP-knowers ($\text{mean}_{\text{not transformed}} = .60$, $n = 16$) than in the group of CP-knowers ($\text{mean}_{\text{not transformed}} = .42$, $n = 26$), but this difference did not reach significance, $t(40) = -1.639$, $p = .11$[3]. Children exhibiting a left-to-right SNA pattern did not differ in age from children exhibiting a right-to-left or no SNA pattern (*ps* > .30, Mann-Whitney U tests).

In the next step, we analyzed whether the SNA score differed between the groups defined by their responses in the Pretended reading task. One-way ANOVA performed on the SNA score, with indicated text direction (left-to-right, no direction, right-to-left) as a between-subject factor, revealed a significant main effect: $F(2,43) = 3.64$, $p = .035$[4]. Whereas the left-to-right “reading” children

2 For observations without weighting the results were approximately the same: $t(45) = 0.087$, $p = .93$, mean (not transformed) = 0.50

3 For observations without weighting, $t(40) = 1.884$, $p = .067$, means (not transformed) = 0.61 vs. 0.42

4 For observations without weighting: $F(2,43) = 3.595$, $p = .036$

revealed no prevalence of any of the SNA patterns (indicated by a moderate ratio score: $M = .56$), the right-to-left "reading" children exhibited reversed SNA (indicated by a low ratio score: mean = .20). In the group of children who revealed no directional reading pattern, the SNA score was rather moderate, like in the left-to-right "reading" group (mean = .52). A similar ANOVA run with the indicated location of text beginning (left, middle, right) as a between-subject factor revealed a main effect on a tendency level, $F(2,43) = 2.902$, $p = .066$[5].

In the final step, we examined whether SNA for numerosities was related to a manual response pattern (ipsilateral vs. contralateral). Similarly to the counting tasks, there were descriptively more ipsilateral than contralateral responses (112 vs. 66, summed up for all children together). These responses dominated in about half of the children (51%). There was also a clear correspondence between the type of response pattern (ipsilateral, contralateral) and the number of SNA-consistent responses (fewer/left, more/right): Among all ipsilateral responses, only 30% (34/112) were consistent with the left-to-right SNA pattern ($\chi^2(1) = 17.286$, $p < .001$), whereas for contralateral responses this percentage increased up to 82% (54/66, $\chi^2(1) = 26.727$, $p < .001$). Thus, the ipsilateral response strategies were associated with a substantial reduction of the culture-consistent number-to-space mapping. The results for this task are summarized in Table 4.

Table 4. The upper part of the table presents the mean proportions (SD) of SNA congruent trials (smaller set assigned to the left side or larger set to the right side) in the Numerosity task, in relation to reading knowledge (referring to text orientation and location of text beginning). All means are not transformed or weighted. The lower part of the table includes raw proportions of SNA congruent trials calculated separately for all ipsi- and contralateral responses recorded for this task

Numerosity task ($N = 46$)			**Average proportion of SNA congruent trials (*SD*)**
Overall			0.50 (0.30)
Reading knowledge	Text orientation	Left-to-right	0.56 (0.27)
		Right-to-left	0.20 (0.27)
		No direction	0.52 (0.30)
	Text beginning	Left	0.53 (0.27)
		Right	0.33 (0.21)
		Middle	0.60 (0.35)
			Raw proportion of SNA congruent trials among all ipsi- or contralateral responses
Manual response pattern		Ipsilateral	0.30
		Contralateral	0.82

[5] For observations without weighting: $F(2,43) = 3.098$, $p = .055$

Discussion

The aim of the present study was to examine how different forms of number-space associations - directional object counting, directional finger counting, and spatial preferences for numerosities - develop in children in a preschool period. We were particularly interested in how these associations are related to children's knowledge about spatial organization of a written text and their manual response pattern in the left and right hemispace.

We observed that spatial-numerical associations emerged in different forms when assessed with different tasks: the left-to-right number-space mapping emerged only in the object counting task, whereas it was reversed in the finger counting task and disappeared in the numerosity task. Furthermore, none of the tested forms of SNA was clearly consistent with cultural knowledge about text orientation. The only case in which "reading" direction was related to a spatial-numerical effect clearly opposed cultural conventions: children who pointed in a right-to-left reading direction also mapped numerosities in a right-to-left manner. Finally, the appearance of culture-consistent (left-to-right) SNA was associated with performing or initiating an action on the side contralateral to the used hand (midline crossing). This relation was common for all SNA measures, but it was most evident for the finger counting task, in which SNA was clearly reversed.

Our findings point to several important issues regarding early formation and development of number-space associations. First, the presented results corroborate the conclusions drawn from previous studies indicating that SNA effects emerge for numerosity comparison (Patro & Haman, 2012), object counting (Shaki et al., 2012), and other spatial-numerical tasks (Knudsen et al., 2015) already before school education. Hence, we have shown once again that explicit reading and writing experience is apparently not necessary in this process. However, we have also shown that SNA effects obtained from different forms of assessment differ from each other in terms of their salience, orientation, and partially also in their susceptibility to spatial reading knowledge and body-related reference frames. This observation indicates that different forms of number-space assessment may in fact refer to different aspects of number-space processing (cf. Patro et al., 2014; Rinaldi et al., 2016). Below, we refer to the main characteristics of each of the three SNA measures to account for the obtained variability in the results.

Direction of object counting

The left-to-right number-space mapping emerged only when it was tested with the object counting task. This result is compatible with the data obtained from adult participants, who usually exhibit more robust SNA in the object counting task (90-100% of adults count from left to right, Opfer & Thompson, 2006; Shaki et al., 2012) as compared to the SNARC effect tested with the magnitude/parity judgment task (only about 70% of adults exhibit a classical

SNARC, Wood et al., 2008). This relative advantage of the object counting task in revealing culture-consistent number-space associations may lie in the explicit spatial characteristic of counting performance. When objects are aligned in a horizontal row, the easiest way to count them is to start from the leftmost or rightmost element and to move towards one direction (starting from the middle element is a rare strategy even among children, e.g. Shaki et al., 2012). In such experimental settings, spatial mapping of numbers is enforced, and only a preference for a particular direction of this mapping is assessed. The direction of counting is transparent, and can be easily learned and memorized already by a preschool child because object counting is a typical cultural activity frequently trained in kindergarten or at home.

Although the dominant counting direction in our study was consistent with the reading conventions of the cultural surroundings (left-to-right), we did not observe any relation between the children's reading knowledge and the direction of their counting. Apparently, the direction in which preschoolers count objects is not necessarily linked to their knowledge about cultural reading conventions. Or, rather, such knowledge develops later than directional counting habits. Indeed, we observed that only 31% of the children indicated that text was organized from left to right, whereas already 65% of children counted from left to right. What then is the major factor that could possibly shape children's directional preferences for counting? One possibility is that even before children acquire directional reading conventions, immersion in certain cultural surroundings could be sufficient to exert influence on children's counting behavior. For instance, children may observe that their parents organize things from left to right or draw objects in that direction (see Lieblich, Ninio, & Kugelmass, 1975; McCrink et al., 2017; Tversky, Kugelmass, & Winter, 1991; Vaid, 1995 for reading-consistent performance of adults in spatial tasks). Another possibility is that children do extract directional knowledge from reading conventions, but they mostly rely on nonverbal cues observed in parents' reading behavior, such as how they turn pages in a book or how they refer to subsequent illustrations, and less on the spatial organization of print (for relatively low focus on print during joint book reading see Evans & Saint-Aubin, 2005; Yaden, Smolkin, & Conlon, 1989). For children who cannot yet read and write by themselves, such nonverbal spatial cues might be much more salient and transparent than the left-to-right configuration of words and sentences in a text. Another possibility to consider is that preliterate children already possess some implicit knowledge about the direction of text organization, and that this knowledge could in fact influenced their counting performance. However, the task that we used in our study required proper understanding of abstract concepts like "beginning/start of the text" and "endpoint of the text", which could not have been properly mastered by children at this age. We cannot also preclude that some of the children counted from left to right because they selected the left hand to perform the task (and not because they preferred to count in a culture-consistent direction). The preference to start on the side ipsilateral to the used hand was well pronounced in our study, but it was not associated with any dominant counting direction (in contrast to children who crossed the body midline, which always counted consistently with the left-to-right cultural pattern). However, as we did not test the direction of the relation between hand and counting direction, we cannot clearly conclude whether the hand influenced the counting pattern in this task or rather the preferred counting pattern influenced a choice of the hand.

Direction of finger counting

In the finger counting task, children mapped numbers starting mostly from the right side (right hand, rightward finger), corroborating previous findings (Knudsen et al., 2015; Newman & Soylu, 2014; Rinaldi et al., 2016; Sato & Lalain, 2008). This direction of counting was in contrast to the left-to-right reading habits dominant in the children's cultural surroundings. Indeed, we did not find any relation between finger counting and reading knowledge.

The obtained result pattern was also opposite to the dominant direction observed in the present study for the object counting task, which suggests that these two number-space effects might be dissociated. Indeed, as previously reported by Rinaldi et al. (2016), the consistency between both counting measures is rather low in a preschool age. Although finger counting and object counting can be classified into one category of the ordinal (counting) SNA, there is a major difference between these tasks: in the first task numbers are mapped onto positions in the external physical space (objects on a table), whereas in the second task they are mapped directly onto one's body parts, in this case fingers. The first SNA measure was only partially related to an ipsilateral response pattern. In the case of finger counting, the role of body becomes more fundamental – the direction in which number-space association is built is fully determined by the order in which we straighten our fingers. When the right hand is selected with its palm faced up, the easiest way is to straighten the thumb first; this strategy results in a clear right-to-left counting pattern. One may hypothesize that the directionality of finger counting could also reflect the way children try to optimize their counting performance in a situation when external objects are not visually presented. When one has to map spoken numerals directly onto fingers, it might be more preferable to orient the hand towards yourself so that all fingers are clearly visible – i.e. with the palm up. Indeed, in our study most of the children were finger-counting by directing their palm towards the body, which could enforce right-to-left directionality in right-hand starters. Thus, an input modality specific to a particular counting task (i.e. visual input from external objects vs. aural input for counting aloud with fingers) could be another aspect differentiating finger and object counting, which could ultimately decide about their directionality. Finally, apart from hand orientation, there was a striking preference for starting with the right hand. There might be at least two reasons explaining the prevalence of this pattern among preschool children. First, this preference could reflect the emerging dominance of the right hand in manual tasks (right-handedness) in this early period of life (Gudmundsson, 1993; McManus et al., 1988). Preschoolers may also partially learn the right-to-left counting pattern by observing how adults count with their fingers. In fact, the finger counting pattern that we observed in children clearly resembled the spontaneous counting pattern observed in adults by Wasner and colleagues (2014). However, it should be noted that counting pattern in adults is context-dependent: it might reverse towards a cultural left-to-right direction when counting preferences are assessed with a computerized questionnaire (in which fingers are additionally depicted in external space – on a computer screen, Lindemann et al., 2011; Wasner et al., 2014).

Altogether, the reported findings suggest that mapping numbers onto physical external space is not equivalent to mapping numbers onto one's own bodily space (fingers), both in terms of direction of this mapping (left-to-right vs. right-to-left) and its putative determinants (cultural conventions vs. bodily factors). This dissociation can be observed not only in adults but also in preschool children.

Spatial arrangement of numerosities

The cardinal SNA for non-symbolic numerosities was the least pronounced spatial-numerical effect: there was no dominant direction of mapping in the tested group of children. This result might indicate that the spatial properties of cardinal numerical magnitudes are less explicit. This difference may lie not only in the specificity of the task (which is usually rarely trained and in which stimuli are not arranged in a row like in the counting task) but also in the general representational characteristic of non-symbolic numerosities (which are imprecise and, therefore, it is more difficult to map them onto distinct spatial locations).

Although no dominant direction was observed for numerosity-to-space mapping, we observed that the direction of this mapping systematically varied on both the inter- and intra-individual levels. First of all, the SNA was partially associated with children's knowledge about text organization. However, in contrast to our predictions, the direction of SNA did not clearly follow developing left-to-right reading habits, but reflected some kind of culture-inconsistent right-to-left preferences. One may suppose that preschool children do not yet possess explicit knowledge about text organization, or at least that this knowledge is not well consolidated enough to be associated with developing number-space mapping (and to exert influences on the direction of this mapping). Nevertheless, the relation observed for right-to-left direction might suggest that some link between spatially oriented activities and SNA may already exist in preliterate children, but that it might not be necessarily cultural in origin. Although early predispositions to link number processing to spatial preferences may primarily function on a more general level, only some sort of systematic cultural training might shape this link in a consistently left-to-right direction. In a study by Patro, Fischer, Nuerk and Cress (2016), preschoolers formed a SNARC-like effect in different directions, depending on whether they were trained beforehand to move an object to the right or to the left. Apparently, the direction of numerosity-to-space mapping in preschool children is flexible and susceptible to spatial experience of different kinds and of different directionality, and this might account for the large variability of individual SNARC-like patterns observed in this age group.

Our results show that preliterate children, on average, might not yet form robust cultural knowledge about text organization. However, this might be only one of several reasons why we did not observe the SNARC-like effect in this age group. Alike in the counting tasks, the left-to-right cardinal SNA was also associated with the type of manual strategy used by the child to execute the task: the culture-consistent number-space mapping was strong and salient when a child responded on the side contralateral to the hand, but it was substantially dimmed when the child responded on the ipsilateral side. Although crossing the body midline was a more effortful strategy, it seems that at least some of the children overcame this difficulty and responded in line with their cultural preferences. But this was not the case for all of the children. On the basis of that, we postulate that the hand with which a child responds in SNARC-like tasks should always be carefully controlled. It might appear that seemingly null effects found in children studies (with no control for the responding hand) do not indicate a lack of number-space coding at this developmental period. Such a coding in preliterate children is indeed a fact that has been documented in several studies. The observed null effects may simply indicate that SNA is strongly related to the manual response strategy used in a task, as it was clearly the case in our study.

Altogether, number-space associations based on cardinal numerical processing were less pronounced and less explicit than other SNA measures. This may be the result of the more implicit spatial characteristic of this form of SNA. We suppose that this makes the SNARC-like effect less stable and more susceptible to other factors like specific spatial preferences of children (looking at pictures or text in a book, drawing objects or arranging toys on a shelf), even if these preferences are not always consistent with cultural conventions. It cannot, however, be excluded that non-symbolic SNARC-like associations – just because of this implicit characteristic - are more likely to emerge in tasks based on implicit measures, like speed of spatial responses or attentional shifts to the left or right (cf. Bulf et al., 2016; Ebersbach et al., 2014; Patro & Haman, 2012), which do not require the explicit arrangement of numerosities in space (like the task used in our study). Furthermore, non-symbolic numerosity-based SNA might also partially depend on the acquisition of cardinal principle knowledge. In line with previous studies (e.g. Patro & Haman, 2012), we observed that the SNARC-like effect was slightly weakened in children who already acquired this knowledge. This may point to some important developmental changes in reorganization within spatial numerical representation caused by acquisition of the symbolic (verbal) number system. All in all, it seems that the mechanisms underlying construction of the numerosity-based SNA may be more complex and more diversified than those underlying other (ordinal) forms of number-space associations.

Conclusions

Number-space associations develop very early in a child's life. Although these associations do not require formal literacy training to develop, they are not always clear and robust among preschool children. They might depend on several factors, including some sort of directional experience, as well as body-related mechanisms. Knowledge about the spatial organization of words and sentences within a text is not necessarily required to form culture-consistent associations, at least not in the case of counting direction. Some authors also postulate that number-space coding is at least partially hardwired and determined by biological factors (de Hevia et al., 2014; Rugani, Vallortigara, & Regolin, 2015; Rugani, Vallortigara, Priftis, & Regolin, 2015).

However, to better understand which factors take part in constructing and shaping number-space associations in different developmental periods, one should realize that number-space mapping is not a unitary phenomenon. Different number-space assessments may lead to different sizes and directions of the SNA effects, even in the same group of children. Also, different number-space associations may have different origins and developmental trajectories, and they might be differently influenced by different factors. Given that, one should always take into account the complexity of number-space associations while examining their early origins and development.

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