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The approximate number system is not predictive for symbolic number processing in kindergarteners

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The relation between the approximate number system (ANS) and symbolic number processing skills remains unclear. Some theories assume that children acquire the numerical meaning of symbols by mapping them onto the preexisting ANS. Others suggest that in addition to the ANS, children also develop a separate, exact representational system for symbolic number processing. In the current study, we contribute to this debate by investigating whether the nonsymbolic number processing of kindergarteners is predictive for symbolic number processing. Results revealed no association between the accuracy of the kindergarteners on a nonsymbolic number comparison task and their performance on the symbolic comparison task six months later, suggesting that there are two distinct representational systems for the ANS and numerical symbols.

Keywords: Number processing development; Comparison; Symbols; Representation; Approximate number system.

Infants are capable of detecting number changes across different modalities and formats (Izard, Sann, Spelke, & Streri, 2009; Lipton & Spelke, 2003). Hereto, it is suggested that they possess an innate number sense (e.g., Cantlon, Platt, & Brannon, 2009). The development of this number sense is commonly assessed with a numerosity discrimination task. Typically, discrimination accuracy increases when two numerosities differ with a larger ratio (e.g., it is easier to discriminate 12 vs. 24, with a ratio of 1:2, than 12 vs. 8, with a ratio of 2:3). This is explained by assuming that numbers are coded as analogue magnitudes (e.g., Piazza & Izard, 2009). These approximate representations obey Weber–Fechner's Law (Fechner, 1860): The precision of a representation is related to the numerical size (smaller numbers are represented more precisely than larger numbers), which decreases the discriminability of larger numbers. Therefore, this ability is referred to as the "approximate number sense" (ANS; Dehaene, 1997). Studies showed that the ANS acuity increases with age: 3–4-year-old children are able to choose the larger of two numerosities with a ratio of 3:4 and gradually become sensitive to a ratio of 7:8 by adulthood (Halberda & Feigenson, 2008; Piazza et al., 2010).

Some theories suggest that the ANS forms the basis for later acquired symbolic number abilities (e.g., Halberda & Feigenson, 2008; Inglis, Attridge, Batchelor, & Gilmore, 2011; Libertus, Feigenson, & Halberda, 2011; Mazzocco, Feigenson, & Halberda, 2011b; Piazza et al.,

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2010). Symbols are thought to be mapped onto the ANS and acquire meaning through the association with the ANS (e.g., Barth, La Mont, Lipton, & Spelke, 2005; Dehaene, 1992; Mundy & Gilmore, 2009). This is supported by behavioural studies investigating children with mathematical difficulties or developmental dyscalculia (DD) who appeared to have problems with discriminating nonsymbolic (e.g., Mazzocco, Feigenson, & Halberda, 2011a) or nonsymbolic and symbolic numerosities (e.g., Landerl, Fussenegger, Moll, & Willburger, 2009; Mussolin, Meijas, & Noël, 2010). People struggling with maths seem to have a core dysfunction of the ANS, resulting in difficulties with the processing of nonsymbolic numbers and with the processing of symbols that are mapped onto the ANS. In typically developing children, also a correlation between ANS acuity and maths achievement has been reported (e.g., Mundy & Gilmore, 2009), but this relationship seems to be stronger for children with lower maths scores than for children with higher maths scores (Bonny & Lourenco, 2012). Libertus, Feigenson, and Halberda (2013) showed that the ANS acuity of 4-year-olds is predictive for maths achievement measured one year later, even when individual differences in maths ability at the initial time of testing is controlled for. However, recently, a study by Fuhs and McNeil (2013) showed that the association between numerosity processing and maths achievement disappears when additional factors such as inhibitory control are taken into account.

Impaired symbolic number comparison but intact nonsymbolic number comparison performance in children with DD (e.g., De Smedt & Gilmore, 2011; Landerl & Kölle, 2009; Rousselle & Noël, 2007) or a correlation between symbolic comparison but not nonsymbolic comparison performance and maths achievement in typically developing children has also been reported (e.g., Cirino, 2011; Holloway & Ansari, 2009; Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013; Sasanguie, Van den Bussche, & Reynvoet, 2012; Vanbinst, Ghesquière, & De Smedt, 2012). These studies suggest that children with mathematical difficulties do not suffer from a dysfunction of their ANS per se, but rather from a problem with accessing that ANS when they are confronted with a numerical symbol (i.e., the "access-deficit"-hypothesis; Rousselle & Noël, 2007). Further support for this mapping hypothesis comes from imaging studies. Piazza, Pinel, Le Bihan, and Dehaene (2007) for instance, investigated whether populations of neurons respond to symbolic (i.e., digits) and nonsymbolic (i.e., dot arrays) stimuli. Participants were first adapted to dot patterns or digits, and then a new number was presented in either the same or a different notation. Piazza et al. (2007) observed a numerical adaptation effect (i.e., less recovery of the functional magnetic resonance imaging (fMRI) blood-oxygen-level-dependent (BOLD) signal after the presentation of a numerically close number and more recovery after a distant number) irrespective of notation change, which supports the idea that symbols are mapped onto the ANS.

In contrast with the mapping idea, it has recently been suggested that there might be two separate but coexisting systems for exact symbolic and approximate nonsymbolic number processing (e.g., Holloway & Ansari, 2009; Noël & Rousselle, 2011). Learning the meaning of number words would lead to the emergence of a new, exact representational system for symbols. Afterwards, this exact symbolic representation would then connect with the preexisting approximate nonsymbolic representation system (Carey, 2001, 2004; Le Corre & Carey, 2007). Noël and Rousselle (2011) argued that the discrepancies between the studies investigating number processing in children struggling with maths can be explained by this hypothesis of two separate representation systems. They propose that an initial deficit in processing symbols in young children might lead to less refinement of the ANS when they grow older. This could explain why only studies that examine older children (i.e., 10–14-year-olds) with mathematical difficulties observed findings in favour of the "ANS deficit"-account (e.g., Mussolin et al., 2010; Piazza et al., 2010). In adults, Lyons, Ansari and Beilock (2012) argued that the association between the ANS and symbols is weaker than commonly assumed.

They showed that adults performed worse on a mixed notation comparison task than on a pure symbolic or a pure nonsymbolic comparison task. According to the authors, these results suggest that switching between notations requires an additional processing cost, possibly due to the fact that two distinct systems are involved. Finally, in a fMRI adaptation study, Cohen Kadosh et al. (2011) observed that the effect of magnitude change was affected by a change in numerical format (e.g., from digits to dot patterns). These findings suggest two distinct, notation-dependent magnitude representations at the neural level.

These behavioural and neuroimaging studies demonstrate that, to date, it remains an open question whether the ANS is the foundation onto which symbolic representations are mapped or whether the ANS and the exact system for symbolic numerosities develop as two distinct representational systems that become connected throughout development. We shed new light on this debate by investigating kindergarteners, because these children just started to acquire knowledge of digits at school. A nonsymbolic comparison task was administered at the beginning of the school year. During the six months after testing, children learned the symbols as part of the school curriculum. After these six months, children were tested again with a symbolic comparison task to explore the relation between their performances on both tasks. At Time Point 2, we also included another nonsymbolic comparison task. If there are two separate systems, no association between the kindergarteners' performance on the ANS task and the symbolic comparison task is expected, because the connections between the systems are still developing in this age group. If, on the other hand, symbols are learned by being mapped onto the ANS, it is hypothesized that there will be an association between the performances on both tasks, because a more precise ANS will be combined with easy mappings of symbols onto that ANS. Furthermore, a correlation between both nonsymbolic tasks was expected and would allow us to exclude that a power problem (i.e., a false equivalence—not enough statistical power to prove the existence of an otherwise real effect at the population level, due to a sampling error/insufficient number of participants) is responsible for the possible absence of a relation between the performance on the nonsymbolic task and the performance on the symbolic task.

Method

Participants

Fifty-three kindergarteners were recruited from three different schools in Flanders, Belgium. Seven children were removed from the analyses because they were too slow or made too many errors (i.e., 3 *SD*s above/below the group average) in one of the tasks. From three children, no data could be obtained at Time Point 2 due to illness or absence at the day of testing. The final sample thus consisted of 43 typically developing children (M_{age} at Time Point 1 = 5 years and 5 months; $SD = 4$ months; 22 females).

Procedure

At Time Point 1 (t_1), the children were tested separately in a quiet room. They performed a nonsymbolic comparison task. Six months later, at Time Point 2 (t_2), the children were tested again with a nonsymbolic comparison task and with a symbolic comparison task. A different version of the nonsymbolic comparison task (i.e., with different number ranges) was used at t_2 compared to t_1 in order to prevent familiarity with one of the tasks. At t_2, the order between the tasks was fully counterbalanced. Children were given a short break between each task. After the experiment, the children received a small reward. Although in the Flemish education system knowledge of the Arabic digits is not officially required in kindergarten, discussions with kindergarten teachers informed us that in reality most teachers already include knowledge of Arabic digits up to five in their educational program during this six-month interval in the third year of kindergarten. Furthermore, the teachers were also convinced that at the end of the third year of kindergarten (i.e., our second test point) all kindergarteners know the Arabic digits from 1–9, despite this not being officially required. Of course, informal learning experiences (e.g., at home) play a role in this as well (LeFevre et al., 2010). Previous studies have already demonstrated that the numerically relevant input that parents provide (i.e., the so-called "parent number talk") may be an important factor in young children's numerical development (e.g., Gunderson & Levine, 2011).

Measures

Nonsymbolic comparison task at t_1. The nonsymbolic comparison task at t_1 was inspired by Halberda and Feigenson's study (2008). Two grey arrays with blue and yellow dots on the left- and the right-hand side, respectively, were simultaneously presented on a 14-inch screen. Each array appeared in a background frame, which was flanked by a picture of a yellow or blue monkey (see Figure 1). The number of dots in each array ranged between 1 and 18. Numerosity pairs from five different numerical ratios were presented: ratio 2 (pairs 1–2 and 3–6), ratio 1.50 (pairs 2–3 and 6–9), ratio 1.33 (pairs 3–4 and 9–12), ratio 1.25 (pairs 4–5 and 12–15), and ratio 1.20 (pairs 5–6 and 15–18). All pairs were presented four times, resulting in a total of 40 test trials. The stimuli were generated using the program developed by Gebuis and Reynvoet (2011), controlling for four visual parameters: (a) the convex hull (i.e., smallest contour around the array of dots); (b) the aggregate surface of the dots; (c) density (i.e., the aggregate surface divided by the convex hull); and (d) the average diameter. Regression analyses confirmed that there was no relationship between each visual cue and numerosity (all R^2s $< .04$, all ps $> .071$). The different visual cues of the stimuli covaried positively with numerosity in half of the trials and negatively with numerosity in the other half.

Prior to testing, the experimenter explained the task to the child using a blue and a yellow cardboard monkey, which were each given a different amount of sweets. The child was asked to verbally indicate which monkey had most sweets. Once the child understood the instructions and responded correctly twice in a row the computerized task was initialized. The child was told that the stimuli would be presented too briefly to be able to count and that she or he had to estimate as quickly and accurately as possible whether there were more blue or yellow "sweets" (i.e., dots). Five practice trials were presented, followed by 40 randomized test trials. Each trial was preceded by a fixation cross (i.e., 600 ms) and was presented for 2,000 ms. Children could respond during the stimulus presentation or during a blank screen that followed the stimulus presentation. The experimenter immediately pressed the corresponding key when a verbal response was given, after which a frame to initiate the next trial appeared. Each trial was started by the experimenter when the child was attentive. To maintain participants' motivation, feedback was provided on every trial by a 1-second high-pitched or low-pitched beep for a correct or incorrect answer, respectively (see Halberda & Feigenson, 2008, for a similar procedure). Stimulus presentation and recording of the data were controlled by E-prime 1.1 (Psychology Software Tools, http://www.pstnet.com).

Nonsymbolic comparison task at t_2. The procedure and task instructions were identical to those of the nonsymbolic comparison task conducted at t_1, but different numerosities were used. One array always contained the reference numerosity of 16 dots, whereas the other array contained 8, 11, 12, 21, 24, or 32 dots, resulting in six possible pairs and three ratios (1.2, 1.5, and 2). Each of the six pairs was repeated four times. Five training trials preceded the 48 randomized test trials. Again, the stimuli were generated using the program developed by Gebuis and Reynvoet (2011), and regression analyses confirmed that there was no relationship between each visual cue and numerosity (all R^2s $< .06$, all ps $> .25$).

Symbolic comparison task. The procedure was identical to that of the nonsymbolic comparison tasks, with the exception that the stimuli were Arabic digits between 1 and 9. The numerical distance between stimuli ranged from 1 to 4, with 10 trials per distance. There was an equal number of pairs for each distance, resulting in a total of 40 trials.

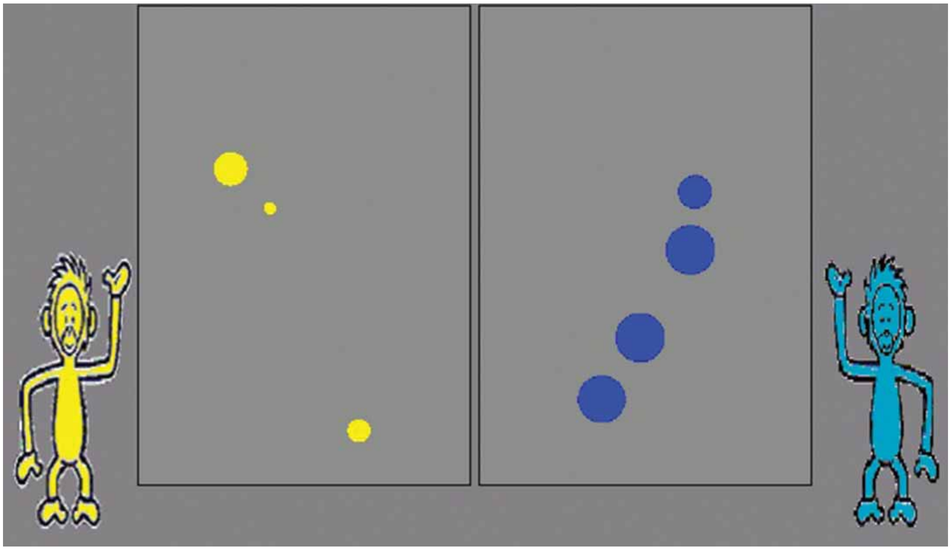

Figure 1. *Sample of test trial used in the nonsymbolic comparison task. Participants indicated whether there were more (yellow) dots on the left or (blue) dots on the right side of the screen. To view a colour version of this figure, please see the online issue of the Journal.*

From this trial list, five practice trials were randomly selected. The children had to indicate which of the two Arabic digits was the larger.

Results

Analogous with previous literature, we analysed the approximate nonsymbolic tasks as a function of ratio (e.g., Halberda, Mazzocco, & Feigenson, 2008), whereas the symbolic comparison task was examined as a function of numerical distance (e.g., Holloway & Ansari, 2009). Mean accuracies were used as an outcome index for all three tasks instead of Weber fractions because, in previous studies, it was observed that in young children the volatile fits of the psychophysical model make the Weber fraction a less useful measure of the ANS precision than the classical correct response rates (e.g., Libertus et al., 2013; Mazzocco et al., 2011b; Mussolin, Nys, Leybaert, & Content, 2012). Moreover, Sasanguie et al. (2013) demonstrated that the Weber fractions and the accuracy rates are highly correlated with each other, suggesting that similar results would have been obtained when Weber fractions would have been used instead of accuracies. Furthermore, correlation analyses were conducted to examine the relationship between the accuracy performances[1] on the three experimental tasks under investigation. By means of a one-way analysis of variance (ANOVA), an effect of presentation order of the tasks at t_2 on children's performance was excluded, $F < 1$ in the case of symbolic comparison performance and $F < 1$ in the case of nonsymbolic comparison performance.

Nonsymbolic comparison at t_1

A repeated measures ANOVA was conducted with ratio (5 levels) as within-subjects factor on children's mean accuracies. The analyses revealed a significant main effect of ratio, $F(4, 39) = 77.46$, $p < .001$, $\eta_p^2 = .89$, showing higher accuracy rates with

[1] Next to the correlations between the accuracy performances, we also calculated the distance and the ratio effects by means of a difference score (i.e., distance 1 – distance 4 for the distance effect in the symbolic task and ratio 1.2 – ratio 2 for the ratio effects in both nonsymbolic tasks) and correlated them with each other. However, none of these correlations were significant (all $rs < .23$, all $ps > .14$).

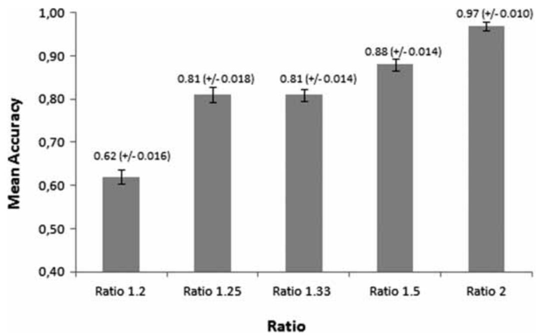

Figure 2. *Nonsymbolic comparison data at Time Point 1, showing higher accuracy rates with increasing ratio. Error bars represent 95% confidence intervals (see Loftus & Masson, 1994).*

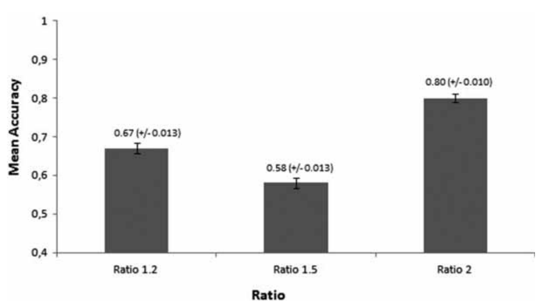

Figure 3. *Nonsymbolic comparison data at Time Point 2, showing higher accuracy rates with increasing ratio. Error bars represent 95% confidence intervals (see Loftus & Masson, 1994).*

increasing ratio (see Figure 2). Pairwise comparisons indicated that performance on all ratios significantly differed from each other (all *p*s $\leq .01$), except for ratio 1.25 and ratio 1.33 ($p = .83$).

Nonsymbolic comparison at t_2

Children's mean accuracies were analysed by means of a repeated measures ANOVA with ratio (3 levels) as within-subjects factor. The analyses revealed a significant main effect of ratio, $F(2, 41) = 63.46$, $p < .001$, $\eta_p^2 = .76$ (see Figure 3). Pairwise comparisons showed that accuracies increased with increasing ratio (all *p*s $< .01$), except for ratio 1.5, on which the accuracy was unexpectedly the lowest.

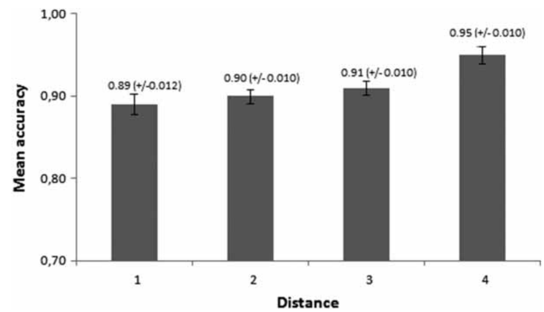

Figure 4. *Symbolic comparison data at Time Point 2, showing higher accuracy rates with increasing distance. Error bars represent 95% confidence intervals (see Loftus & Masson, 1994).*

Symbolic comparison at t_2

A repeated measures ANOVA was conducted with distance (4 levels) as within-subjects factor on children's mean accuracies. Results revealed a significant main effect of distance, $F(3, 40) = 4.43$, $p < .01$, $\eta_p^2 = .25$, showing higher accuracy rates with increasing distance (see Figure 4). Pairwise comparisons demonstrated significant differences between the distances (all *p*s $< .04$), except for distance 1 versus distance 2 ($p = .44$), distance 2 versus distance 3 ($p = .28$), and distance 1 versus distance 3 ($p = .11$).

Correlation analyses

Correlation analyses were conducted on the accuracy scores for each of the tasks. A significant correlation between the accuracy on the nonsymbolic comparison tasks at t_1 and t_2 was present, $r(41) = .46$, $p < .001$, indicating a similar performance on both tasks.[2] No relation was found between the nonsymbolic comparison task at t_1 and the symbolic comparison task six months later, at t_2, $r(41) = .22$, $p = .16$. Also the correlation between the symbolic comparison task and the nonsymbolic comparison task at t_2 was not significant, $r(41) = .09$, $p = .59$.

In order to exclude that the different numerosity range used in the nonsymbolic comparison task conducted at t_1 and the symbolic comparison task

[2] When considering only the relatively larger trials of the nonsymbolic comparison task at t_1 (i.e., excluding the subitizable quantities), the correlation between the performance on the nonsymbolic comparison task at t_1 and t_2 remained significantly present, $r(41) = .45$, $p < .001$.

conducted at t_2 caused the absence of a correlation between the performances on both tasks, we examined the correlation between the overall performances on both tasks when only those trials that were identical in the two tasks were taken into account (i.e., only trials 1–2, 2–3, 3–4, 4–5, 5–6). These analyses confirmed that there was no correlation, $r(41) = .13$, $p = .39$. Moreover, when considering only the relatively larger trials of the nonsymbolic comparison task at t_1, again, no correlation with the overall symbolic comparison performance was present, $r(41) = .12$, $p = .45$, and, importantly, there was a significant positive correlation between the performance on the small-number trials and the large-number trials of the nonsymbolic comparison task at t_1, $r(41) = .33$, $p = .03$, indicating that the children performed similarly in both number ranges.

Discussion

The relation between the approximate number system (ANS) and symbolic number processing is debated. The current study contributed to the debate about whether the ANS is the foundation onto which symbolic representations are mapped or whether the ANS and the exact system for symbolic numerosities are two distinct representational systems by examining the performance of kindergarteners who had only just acquired knowledge of digits. If these are two separate systems, no association between the performances on both tasks is expected, due to the absence of a strong connection between the two systems. If an association between these systems is observed in older children or adults, it would not be possible to disentangle whether one underlying representation is responsible or whether this relation is due to a strong connection between the ANS and the symbolic number system that has been established throughout development.

Importantly, the accuracy of the kindergarteners on the ANS task at t_1 (i.e., three months after the start of the school year) was not predictive for their performance on the symbolic comparison task six months later at t_2 (i.e., the end of the school year). Additionally, children's performance on the symbolic comparison task and the ANS task at t_2 were uncorrelated. Moreover, these results remained highly similar when only those trials that were identical in both the ANS task and the symbolic task were taken into account. These results support the view of two separate representational systems for the ANS and symbolic numbers (e.g., Noël & Rousselle, 2011). If the symbols that the kindergarteners have learned during the six-month interval were mapped onto the ANS, a correlation between the performances on both tasks should be present. The current findings are in line with previous cross-sectional studies with kindergarteners (e.g., Sasanguie, De Smedt, Defever, & Reynvoet, 2012) and older children (e.g., Holloway & Ansari, 2009; Vanbinst et al., 2012), which did not observe an association between the performance in nonsymbolic and symbolic comparison tasks and also interpreted this as evidence for possible different underlying representations. Moreover, this observation is in line with the growing amount of studies observing the absence of an association between the ANS acuity and symbol-based mathematics performance (e.g., Iuculano, Tang, Hall, & Butterworth, 2008; Price, Palmer, Battista, & Ansari, 2012; Sasanguie et al., 2013; but see Libertus et al., 2013) or early symbolic number abilities such as counting, Arabic number knowledge, and number word identification at a young age (i.e., 5–6 years; e.g., Mussolin et al., 2012).

Two different versions of the ANS task were presented to the kindergarteners in order to prevent familiarity with the task. Despite the different number ranges and the possible influences of subitizing processes (Trick & Pylyshyn, 1994), an association was observed between the performance on the nonsymbolic comparison task conducted at t_1 (i.e., with stimuli including the subitizing range, 1–18) and the performance on the task conducted at t_2 (i.e., with nonsymbolic stimuli beyond the subitizing range, 8–32). When excluding the subitizable quantities from the task at t_1, the correlation between the performance on both tasks remained present. This suggests that both ANS tasks are reliable measures of the same construct —namely, kindergarteners' nonsymbolic number processing. In addition, these results confirm that the absence of an association between ANS acuity and symbolic number processing is not due to a power problem (i.e., insufficient number of participants).

Finally, a limitation of this study is that we did not control for Arabic digit knowledge at our first time point (t_1—i.e., the first trimester of third year of kindergarten). Consultations with kindergarten teachers informed us that this time point was ideally suited to start with the examination of the children in order to assess our hypothesis. However, diverse environmental factors outside the formal education system (e.g., home learning environment, parent number talk; Gunderson & Levine, 2011; LeFevre et al., 2010) could have influenced the Arabic digit knowledge of the kindergarteners so far. Consequently, it cannot be ascertained that some of the children did not know yet some of the Arabic digits at t_1. Nevertheless, as the informal learning experiences of children most likely differ, we believe that the experiences of the teachers in the formal education system are a good and reliable reference point.

Together, these data suggest that the ANS and the symbolic number system do not gradually diverge from each other in adulthood, as suggested by Lyons and colleagues (2012), but support the hypothesis of two distinct representational systems present from the age of 5 years.

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