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The Development of Arabic Digit Knowledge in 4- to 7-Year-Old Children

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Abstract

Recent studies indicate that Arabic digit knowledge rather than non-symbolic number knowledge is a key foundation for arithmetic proficiency at the start of a child's mathematical career. We document the developmental trajectory of 4- to 7-year-olds' proficiency in accessing magnitude information from Arabic digits in five tasks differing in magnitude manipulation requirements. Results showed that children from 5 years onwards accessed magnitude information implicitly and explicitly, but that 5-year-olds failed to access magnitude information explicitly when numerical magnitude was contrasted with physical magnitude. Performance across tasks revealed a clear developmental trajectory: children traverse from first knowing the cardinal values of number words to recognizing Arabic digits to knowing their cardinal values and, concurrently, their ordinal position. Correlational analyses showed a strong within-child consistency, demonstrating that this pattern is not only reflected in group differences but also in individual performance.

Keywords: Arabic digits, magnitude, cardinality, ordinality, development

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The remarkably creative and flexible use of a vast array of symbols is a unique and distinctively human talent (DeLoache, 2002). Becoming symbol-minded, therefore, is a crucial developmental task a child has to master in order to participate in the cultural life of its society. In the domain of numerical cognition such symbolic understanding refers to the general skill of correctly referencing specific quantities both by number words ('three' cookies) and by Arabic digits ('3' cookies).

Many studies have looked at whether children map newly acquired symbolic representations of number onto their pre-existing non-symbolic representations of number (the approximate number system; Dehaene, 1992; Feigenson, Dehaene, & Spelke, 2004) and how either of these representations relates to math achievement in later years. Even though some studies found significant relationships between performance in non-symbolic number tasks and math achievement, the majority of studies have failed to find such a relationship (see De Smedt, Noël, Gilmore, & Ansari, 2013, for a review). Instead, these studies show that when children are tested in both, non-symbolic and symbolic numerical tasks using Arabic digits, individual differences in math achievement are explained by children's symbolic rather than non-symbolic number skills from the preschool period onwards (Bartelet, Vaessen, Blomert, & Ansari, 2014; Göbel, Watson, Lervåg, & Hulme, 2014; Holloway & Ansari, 2009; Sasanguie, De Smedt, Defever, & Reynvoet, 2012; Sasanguie, Van den Bussche, & Reynvoet, 2012). For example, in the study by

Bartelet et al. (2014), the efficiency with which preschool children compare the magnitudes of Arabic digits, but not non-symbolic numbers (arrays of dots), was a consistent predictor of children's arithmetic skills (adding and subtracting) at school entry. With regard to preschool children, Mussolin, Nys, Content, and Leybaert (2014) showed that the ability to recognize, name and compare the magnitude of Arabic digits predicts individual differences in the ability to compare the magnitude of non-symbolic numbers (sets of train wagons), but not vice versa. Consistent with these results, Göbel et al. (2014) found the ability to identify Arabic digits (mapping number symbols to number words) at school entry was a strong predictor of growth in arithmetic skills across the following school year.

These findings are consistent with the view that the link between non-symbolic and symbolic representations of number becomes weaker at some point in development. In a study by Lyons, Ansari, and Beilock (2012) adults' performance in a magnitude comparison task was markedly worse when they had to compare two quantities that were represented by one non-symbolic (dot patterns) and one symbolic (Arabic digits or number words) display, than when they had to compare quantities that were both represented by symbolic displays (Arabic digits and number words). A recent study by Park, Li, and Brannon (2014) using functional magnetic resonance imaging supports this view and shows that the weakening of the link between non-symbolic and symbolic representations of number in children occurs between 4 and 6 years of age. They further found a strong negative correlation of age with the degree of effective connectivity between the right superior parietal lobe (involved in general number processing) and the left supramarginal gyrus (involved in Arabic digit processing and the conversion of orthographic into phonological codes). This suggests that that the initial acquisition of Arabic digits involves the verbal system (number words) but as children become more familiar with Arabic digits they rely less on verbal mediation.

Together, these recent studies indicate that the acquisition of Arabic digits, especially the ability to access and translate exact magnitude information (cardinality) between number words and Arabic digits is a key foundation for arithmetic proficiency at the start of a child's mathematical career. However, to our knowledge, no study has yet investigated the developmental trajectory of children's acquisition of Arabic digit knowledge.

To date, basic developmental achievements with regard to Arabic digit knowledge have been investigated in different studies using varying number ranges, age groups and tasks, such as recognizing Arabic digits (e.g. Whyte & Bull, 2008), mapping number words to digits (e.g. Benoit, Lehalle, Molina, Tijus, & Jouen, 2013), ordinality comprehension of Arabic digits (e.g. Vogel, Remark, & Ansari, 2015), as well as tasks assessing whether children have implicit and explicit access to magnitude information of digits (e.g. Hoffmann, Hornung, Martin, & Schiltz, 2013). These various components of Arabic digit knowledge have not yet been investigated simultaneously within a single investigation with comparable number ranges and across a broad range of age groups, covering preschool as well as school-aged children. The current study aimed to fill this gap. This study, therefore, offers an exploratory and descriptive approach rather than being entirely theoretical in nature.

Using a cross-sectional design, we examined how 4- to 7-year-old children handle Arabic digits in a series of tasks differing in magnitude manipulation requirements that range from digit recognition to implicit as well as explicit access to magnitude information. There were two main objectives. First, to have a closer look at Arabic digit knowledge during the preschool period (4- and 5-year-olds) and school entry (6- and 7-year-olds) by using a variety of different tasks. Second, to reveal developmental trajectories towards Arabic digit knowledge. We choose this particular age range because children start to learn about Arabic digits in this time period; hence, developmental shifts with regard to Arabic digit knowledge likely occur during this time window. Since most children in

Germany enter school at either 6 or 7 years of age, we included both age groups, anticipating possible performance differences between these two age groups.

Five tasks were used to assess children's Arabic digit knowledge. These tasks are presented here in the order in which they were presented to the children, together with the rationale behind their choice and ordering. First, in the *line-bisection task* (LBT) participants swiftly had to bisect lines that were flanked by the Arabic digits 2 and 5 that had similar shapes but different magnitude meanings. Systematic manipulation of the flanker digit positions allowed us to attribute bisection biases to implicit processing of number meaning. Of interest was whether participants would process the magnitude of these digits implicitly although the position of the digits (whether 2 was left and 5 was right of the line or vice versa) as well as their magnitude were irrelevant to the task. Previous studies with adult participants have shown that implicit processing of magnitude information in number line-bisection tasks influences the spatial perception of line lengths, leading to a bisection bias towards the larger number (de Hevia, Vallar, & Girelli, 2008; Fischer, 2001). De Hevia and Spelke (2009) found that 5- and 7-year-old children showed this bisection bias when lines were flanked by non-symbolic numbers (2 and 9 dots). Seven-year-old children were also tested with Arabic digit flankers (2 and 9) but the bisection bias did not occur. These results suggest that implicit access to magnitude information of Arabic digits develops after the age of 7. However, Hoffmann et al. (2013) recently found that already 5-year-old children accessed magnitude information of Arabic digits ranging from 1 to 9. In their study, 5.5- and 5.8-year-old children performed two tasks, one requiring explicit access to magnitude information of the digits (magnitude judgment task) and one involving implicit access to magnitude information of the digits (digit color judgment task). In the magnitude judgment task children decided whether a centrally presented digit was smaller or larger than 5. In the digit color judgment task, children decided whether a centrally presented digit was red or green. Results revealed number meaning activation in both tasks: there was a distance effect (Moyer & Landauer, 1967) for both age groups in the magnitude judgment task. That is, the larger the numerical difference between the presented digit and the reference, the quicker children decided whether the presented digit was smaller or larger than 5. In the digit color judgment task, 5.8-year-old children showed a SNARC effect (Spatial Numerical Association of Response Codes; Dehaene, Bossini, & Giraux, 1993) indicative of magnitude-space mapping. They responded faster to smaller digits with their left hand and faster to larger digits with their right hand. The 5.5-year-old children, however, only showed a SNARC effect when they had done the magnitude judgment task first. These data suggest that 5-year-old children can access magnitude information of Arabic digits explicitly and that explicit access develops slightly before implicit access to magnitude information of Arabic digits in 5-year-old children.

The study by de Hevia and Spelke (2009) and the study by Hoffmann et al. (2013) used different tasks and produced contrasting results. In the line bisection task used by de Hevia and Spelke (2009) number information could be ignored whereas in the digit color judgment task applied by Hoffmann et al. (2013) children's attention was drawn to at least one aspect (color) of the numbers, though not to their magnitude meaning. However, it may be that 5-year-old children also process magnitude information of Arabic digits implicitly in a line bisection task, when Arabic digit flankers are used with which these children are more familiar (e.g. 2 and 5). Our second task was the *digit naming task* (DNT), which measured how many Arabic digits (1 through 6) children were able to recognize and to name with the correct number word. Children were shown each of the digits 1 to 6 in random order and were asked to name them. This task was administered in order to evaluate how many of the digits children were able to recognize.

Third, in the *Digit sorting task* (DST) children were given cards depicting Arabic digits and asked to lay out all the digits in correct order. This task was administered in order to evaluate whether the children understood the obligatory sequencing of digits. With increasing age, children should identify more digits in the DNT and lay out more digits in correct order in the DST. Further, children who lay out all 6 digits correctly may do so in accordance with a left-to-right direction of the mental number line, as observed in Western adults (Shaki, Fischer, & Göbel, 2012; Tversky, Kugelmass, & Winter, 1991). Fourth, the *Arabic digit Give-N task* (ADGive-N task; modeled after Wynn, 1990; see also Sarnecka & Carey, 2008) allowed us to investigate how many Arabic digits children know the cardinal value of, as well as to compare children's knowledge of the cardinality of both Arabic digits and number words. In the task, children were shown the digits in ascending order and asked, for each digit, to feed a stuffed toy bear with 'that many hazelnuts'. When children failed twice to produce the correct amount of hazelnuts the task proceeded by asking the child verbally ('Can you give the bear five hazelnuts?'). Because children contend with number through counting verbally and therefore acquire their first symbolic number representations in the verbal domain (number words), we expected the younger age groups to be more successful in response to number words than to Arabic digits.

Fifth, in the *size congruity task* (SCT), we measured at what age children differentiate between physical and numerical magnitude. Children were asked to compare the Arabic digits 2 and 5 in two different font sizes and to point towards the digit that gives the bear more nuts. Children had to ignore the salient physical magnitude of the digit and only respond to its numerical magnitude. In the task, children were shown the digits 2 and 5 congruently with regard to their physical and numerical magnitude (5 2) as well as incongruently with regard to their physical and numerical magnitude (5 2). In contrast to previous studies involving speeded responses (Bugden & Ansari, 2011; Gebuis, Kadosh, de Haan, & Henik, 2009; Girelli, Lucangeli, & Butterworth, 2000; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002) children in our study responded on their own accord. Of interest was whether they would be incorrect more often in incongruent trials and point towards the physically rather than the numerically larger digit, as compared to congruent trials.

To summarize, the LBT measures implicit access to magnitude information of Arabic digits, whereas the ADGive-N and the SCT measure explicit access to magnitude information of Arabic digits. The SCT may well be more difficult compared to the ADGive-N task, since children have to ignore the perceptually salient physical size of the digits in order to give the correct answer. Based on previous results (Hoffmann et al., 2013), we expected preschool children from 5 years onwards to process magnitude information of Arabic digits implicitly and show a bisection bias in the LBT, as well as to know the cardinal value of the Arabic digits 1 through 6 and succeed in the ADGive-N task. Finally, since the SCT is expected to be more difficult than the LBT and the ADGive-N task, preschool children may perform worse in the SCT than children who already had entered school due to learning experience through direct instruction. For all tasks, except for the LBT, we expected 7-year-old children to perform at ceiling since they most likely already had mastered the Arabic digits 1 through 6. Performance is compared between age groups for each task and across tasks on a group level as well as on an individual level to reveal individual differences in the proficiency of Arabic digit knowledge.

Method

Participants

As shown in Table 1, a total of 88 children in four age groups took part in the study.

Table 1

Participant Demographics

	n	Gender	Mean age (months)	*SD*	Handedness
4-year-olds	23	13 female	51.4	3	21 right, 1 ambidextrous
5-year-olds	23	13 female	65.4	3.2	15 right
6-year-olds	22	11 female	77.4	3	17 right, 1 ambidextrous
7-year-olds	20	10 female	87.9	3.8	17 right

Of the 6-year-old children, there were 15 children who already had entered primary school (n = 15, 8 female, M_{age} = 77.9 months, SD = 3.1, 12 right handed). Participants were recruited and tested in kindergartens (4- and 5-year-olds) in the Saarbrücken area of Germany and in the Developmental Psychology Unit (6- and 7-year-olds), Saarland University, Germany.

Nine additional children were tested but excluded from analyses, because of technical failure (two 4-year-olds, one 5-year-old), shyness (two 4-year-olds, one 5-year-old), unwillingness (one 4-year-old, one 7-year-old) or insufficient knowledge of German language (one 5-year-old). Two children had to be excluded from individual tasks because of unwillingness (LBT: one 4-year-old) or because of experimenter error (ADGive-N, for the verbal measure only: one 5-year-old).

Materials and Procedure

A single testing session comprised the five tasks in the following order: *Line bisection task* (LBT), *Digit naming task* (DNT), *Digit sorting task* (DST), *Arabic Digit Give-N task* (ADGive-N) and the *Size congruity task* (SCT). The tasks were administered in a fixed order to minimize learning effects for the maximum number of tasks possible. Most importantly, starting with the line bisection task allowed us to measure children's implicit access to magnitude information independent of their Arabic digit knowledge measured by the following tasks. Children never received feedback about the correctness of their responses.

Line Bisection task (LBT) — As shown in Figure 1, a horizontal black line, 1 mm in width and 80 mm in length with Arabic digit flankers 2 and 5 (Calibri, font 18), which appeared 1 mm to the left and right of the line, was presented in 8 horizontally shifted positions on a landscape-oriented A6-sized sheet which was centered in front the child. Children received 16 trials, with the side of the larger number counterbalanced across trials and with the position of the line randomized across trials. Before the experimental trials started, the task was shown to the child by the experimenter bisecting two plain lines. Then, the child was to bisect two plain lines and immediately proceeded to bisecting the 16 trials with lines flanked by the digits; every trial was presented on a new sheet of paper. No information pertaining to the digits was provided. The mean deviation from zero (midpoint of the line) was calculated and this mean bias was compared between trials with the larger digit on the left side of the line and trials with the larger digit on the right side of the line.

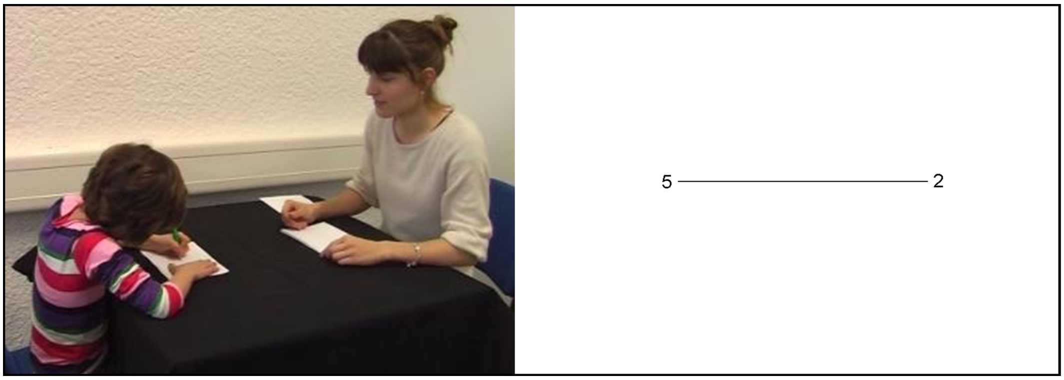

Figure 1. Left panel: Child and experimenter during the *line bisection task* (LBT). Right panel: Example of one sheet used in the LBT.

Digit naming task (DNT) — Children were shown six cards (laminated sheets of A5-sized paper with numbers printed in portrait format in the center using Arial font 280) depicting the Arabic digits 1 through 6 (one digit per card) twice in random order. They were asked for each digit 'What is this?' The mean number of digits children were able to identify was calculated.

Digit sorting task (DST) — In each of two trials children were handed over a set of cards (digits 1 through 6, cards were the same as in the DNT) and asked to lay the cards out on the table in correct order. In each set of cards (one set per trial), the digits were shuffled (A: 2-6-1-3-4-5 and B: 6-1-5-4-3-2). The order of sets (shuffling A first, shuffling B first) was randomized across children in each age group. The mean length of correctly ordered sequences was compared across age groups, as well as the number of children per age group who were able to lay out all six digits in a correct order. Additionally, for those children who laid out all six digits in a correct order, it was coded whether they laid out the digits left to right (L-R) or right to left (R-L).

Arabic digit Give-N task (ADGive-N) — In this version of the Give-N task (Wynn, 1992, see also Sarnecka & Carey, 2008) children were asked to feed a stuffed toy bear (13 cm) with hazelnuts. Materials used were a paper plate (23 cm in diameter), a white plastic bowl (2.5 cm high, 12 cm in diameter) containing ten hazelnuts, and a set of cards (digits 1 through 6, cards were the same as in the DNT). The experimenter held up a card, starting with the digit 1, and asked the child to "put that many hazelnuts on the bear's plate". After the child responded, the experimenter showed the card again and asked if there was the same amount of hazelnuts on the plate. If the child gave the right amount the experimenter proceeded with N+1, with the highest digit asked being 6. If the child responded incorrectly on the second trial at level N, the experimenter proceeded with N-1. Children had to succeed twice on a given digit to qualify as knowing the cardinal value of that digit. Conversely, children had to fail twice on a given digit to qualify as not being able to produce the cardinal value of that digit. For example, when a child failed on digit 5, digit 4 was presented again and the child had to be correct on their second attempt in order to qualify as knowing the cardinal value of the digit 4. Subsequently, digit 5 was presented again and the child had to fail on their second attempt in order to qualify as not knowing the cardinal value of the digit 5.

Since children who fail to produce the correct amount of hazelnuts when seeing a written numeral may well know its cardinal value when hearing the number word, the experimenter proceeded after two failures for a given digit by asking the child verbally (ADGive-N_v). For example, if a child succeeded two times when seeing the digit 4,

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but failed two times when seeing the digit 5, the child was asked ‘Can you give the bear five hazelnuts?’ Also with the verbal procedure children needed to succeed twice on a given number word to qualify as knowing the cardinal value of that number word.

The mean of correctly assigned nuts when presented (1) Arabic digits and (2) number words was compared separately as well as to each other across age groups.

Size congruity task (SCT) — As shown in Figure 2, in four trials children were shown the digits 2 and 5 printed in black Arial font, centered in the horizontal plane on each half of an A4-sized sheet of white paper in landscape orientation. The digits differed in size (large: font 280 and small: font 140) and could be either congruent (5 2) or incongruent (5 2) with respect to their physical and numerical magnitude. Half of the children started with two congruent trials, followed by two incongruent trials and the other half of the children received the reversed order. In both congruent and incongruent trials, the position of the digits (left/right) was counterbalanced as well. On each trial children were asked ‘What digit gets the bear more nuts?’ The mean number of correct congruent trials was compared to the mean number of correct incongruent trials.

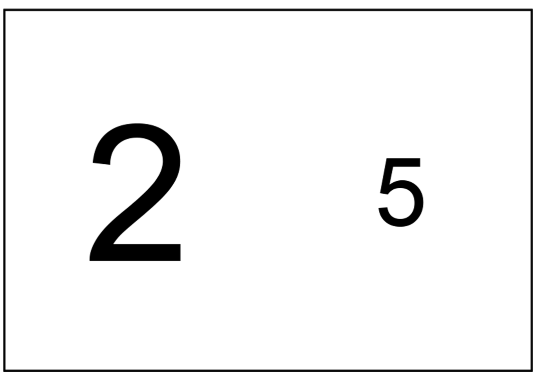

Figure 2. Example of an incongruent trial in the *size congruity task* (SCT).

Results

For all analyses, a significance level of α = 0.05 was used and all *p*-values reported are two-tailed.

Comparisons Between Age Groups for Each Task

Line Bisection task (LBT) — Participants with a mean bias of two standard deviations below or above the group mean bias were considered outliers and excluded from analyses (one 4-year-old, two 5-year-olds, two 6-year-olds and two 7-year-olds).

The mean deviation from zero in cm for trials with the digit 5 on the left of the line was compared to the mean deviation from zero in cm for trials with the digit 5 on the right of the line. As depicted in Figure 3, all age groups, except for the 4-year-old children, showed an overall bias towards the left of the line’s midline (known as pseudoneglect; Jewell & McCourt, 2000). Per age group, *t*-tests comparing the mean bias (mean deviation from zero in cm) between the larger digit positioned right of the line (5 right) and the larger digit positioned left of the line (5 left) revealed a significant bias towards the larger digit for the 5- and 7-year-olds ($t(20) = 2.138$, $p = .045$, Cohen’s $d = 1.07$; $t(17) = 4.391$, $p < .001$, $d = 2.03$), but not for the 4- and 6-year-olds ($t(21) = -1.146$, $p = .27$, $d = .5$; $t(19)$

= .38, p = .71, d = .15, respectively). However, when analyzing 6-year-olds who already entered primary school separately, results revealed a bias towards the larger digit, which was approaching significance, $t(13) = 1.861$, p = .085, d = .81.

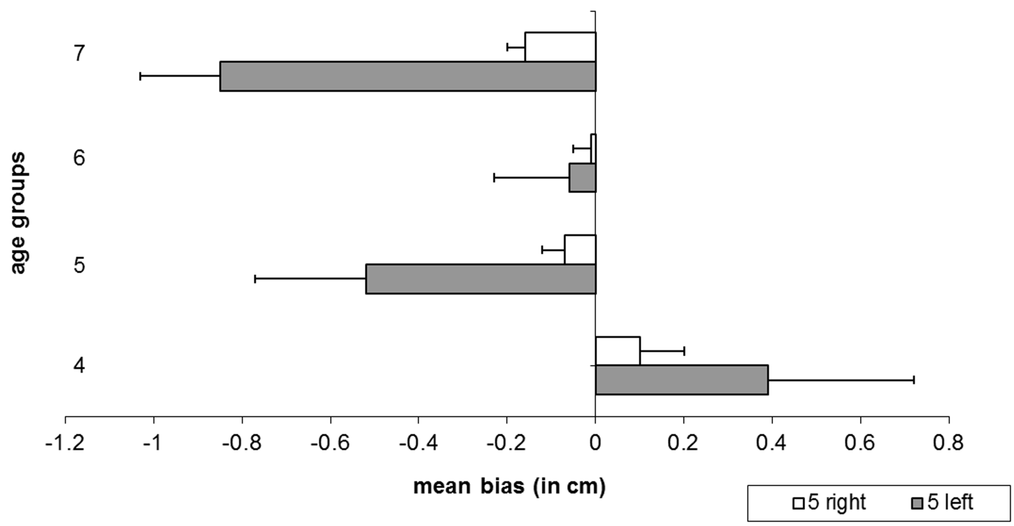

Figure 3. Line Bisection Task. Mean bias (mean deviation from zero in cm) for bisected lines with larger digit to its right (5 right) and larger digit to its left (5 left) as a function of age. Error bars represent standard errors of the means.

Digit naming task (DNT) — As shown in Figure 4, across two trials, mean number of number words correctly assign to the Arabic digits 1 through 6 differed significantly as a function of age, Kruskal-Wallis, $\chi^2(3, 88) = 44.57$, $p < .001$. While all 6- and 7-year-olds identified all digits correctly, 4-year-olds (M = 3.4) identified fewer than 5-year-olds (M = 5.5), who identified fewer than 6-year-olds, Mann-Whitney U's, $p < .001$, r = .55 and p = .043, r = .3, respectively. The percentages of children identifying the digits at least once across two trials were, for the 4-year-olds: 17.4% identified none, 1 = 4.3%, up to 2 = 13%, up to 3 = 4.3%, up to 4 = 21.7%, up to 5 = 8.7% and 30.4% identified all the digits; for the 5-year-olds: 1 = 4.3%, up to 3 = 4.3%, up to 4 = 4.3%, up to 5 =4.3% and 82.6% identified all the digits.

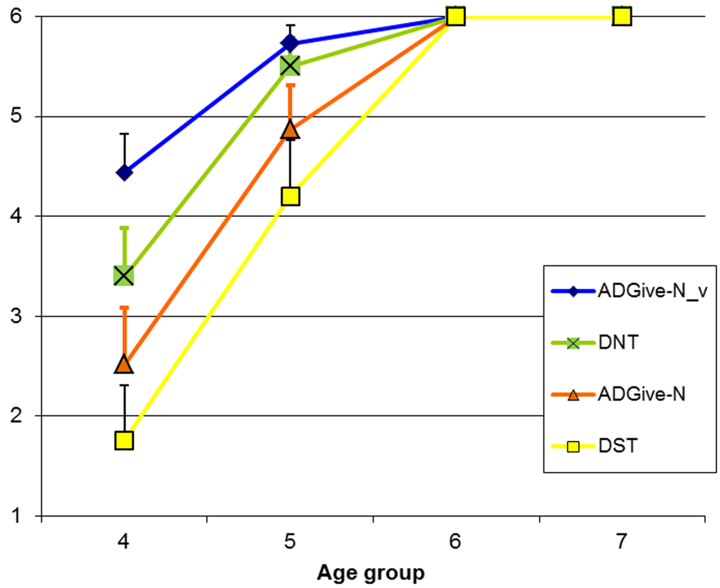

Figure 4. Mean number of Arabic digits (DNT: number words correctly assigned to the digits; DST: amount of digits laid out in a correct order; ADGive-N: correct cardinal values produced for digits) and number words (ADGive-N_v: correct cardinal values produced for number words) across tasks as a function of age. Error bars represent standard errors of the means.

Digit sorting task (DST) — Across two trials, the mean number of Arabic digits children were able to lay out in correct order increased with age, Kruskal-Wallis, $\chi^2(3, 88) = 40.21$, $p < .001$. While all 6- and 7-year-olds laid out all digits correctly, 4-year-olds ($M = 1.76$) laid out fewer digits in correct order than 5-year-olds ($M = 4.2$), Mann-Whitney U, $p = .006$, $r = .41$, and 5-year-olds laid out fewer digits correctly than the 6-year-olds, Mann-Whitney U, $p = .003$, $r = .45$ (see Figure 4). Of the 4-year-olds, 56.5% were not able to lay out any digit in the correct ordinal position at least once across the two trials, 13% laid out the digit 1 in the correct position (either left or right) and 30.4% laid out all digits in the correct ordinal position. Of the 5-year-olds, 21.7% did not lay out any digit in the correct ordinal position at least once across the two trials, 4.3% laid out the digit 1 in the correct ordinal position, 4.3% laid out the digits 1 and 2 in correct ordinal position and 69.6% laid out all digits in the correct ordinal position.

Likewise, the number of children that were able to lay out all digits from 1 through 6 in a correct order in both trials increased with age, $\chi^2(3, 88) = 40.54$, $p < .001$, $\varphi = .68$: six (26%) 4-year-olds succeeded compared to fifteen (65%) 5-year-olds, $\chi^2(1, 46) = 7.09$, $p = .017$, $\varphi = .39$, and fewer 5-year-olds (65%) succeeded than 6-year-olds (100%), $\chi^2(1, 44) = 8.93$, $p = .004$, $\varphi = .45$.

Of all successful trials, the order (L-R, R-L) in which children laid out the digits was also coded. Of those children who laid out all digits in a correct order in both trials, the majority of children in each age group was consistent in the order in which they laid out these digits (4-year-olds: 100%, 5-year-olds: 87%, 6-year-olds: 96%, 7-year-olds: 100%). Of those consistent children, the majority in each age group laid out the digits L-R rather than R-L (4-year-olds: 83%, 5-year-olds: 85%, 6-year-olds: 86%, 7-year-olds: 95%).

Arabic Digit Give-N task (ADGive-N) — Children's ability to produce correct cardinal values for the digits 1 through 6 increased with age, Kruskal-Wallis, $\chi^2(3, 88) = 40.79$, $p < .001$. While all 6- and 7-year-olds produced correct cardinal values for all digits, 4-year-olds (M = 2.52) produced fewer correct cardinal values than 5-year-olds (M = 4.87), who produced fewer correct cardinal values than 6-year-olds, Mann-Whitney U's, $p < .003$, r = .45, p = .006, r = .41, respectively. Of the 4-year-olds, 43.5% did not know the cardinal value of any of the digits, 13% knew the cardinal value of the digit 1, 4.3% knew the cardinal values of digits up to 4, 13% up to 5 and 26.1% knew the cardinal values of all the digits. For the 5-year-olds, 13% did not know the cardinal value of any of the digits, 4.3% knew the cardinal values of digits up to 2, 4.3% up to 4, 8.7% up to 5 and 69.6% knew the cardinal values of all the digits.

Likewise, children's ability to produce correct cardinal values for number words (ADGive-N_v) increased with age, Kruskal-Wallis, $\chi^2(3, 87) = 25.66$, $p < .001$, with 6- and 7-year olds being correct for all number words. Four-year-olds (M = 4.44) produced fewer correct cardinal values than 5-year-olds (M = 5.73), Mann-Whitney U, p = .009, r = .39. Five-year-olds produced fewer correct cardinal values than 6-year-olds, which was marginally significant, Mann-Whitney U, p = .076, r = .27 (see Figure 4). Of the 4-year-olds, 4.3% knew the cardinal value for the number word one, 17.4% knew the cardinal values up to the number word two, 17.4% up to the number word three, 4.3% up to the number word four, 4.3% up to the number word five and 52.2% knew the cardinal values of all the number words. Of the 5-year-olds, 4.3% knew the cardinal values up to the number word two, 8.7% up to the number word 5 and 82.6% knew the cardinal values of all the number words.

As shown in Figure 4, 4- and 5-year-old children were able to produce more cardinal values when asked verbally than when presented with Arabic digits. In order to analyze whether this difference decreases with age, a difference score (d) was calculated (mean number correctly produced cardinal values in response to number words minus mean number correctly produced cardinal values in response to digits). The mean difference scores decreased with age, Kruskal-Wallis, $\chi^2(3, 87) = 39.54$, $p < .001$, with a significant decrease between 4-year-olds (d mean = 1.92) and 5-year-olds (d mean = .86) and 5-year-olds and 6-year-olds, Mann-Whitney U, p = .006, r = .41, p = .019, r = .35, respectively.

Size congruity task (SCT) — The order (congruent first/incongruent first) in which the trials were presented did not reliably affect performance in any of the age groups, Mann-Whitney U, p's > .72.

When comparing the mean number of correct congruent trials (n = 2) to the mean number of correct incongruent trials (n = 2), 4- and 5-year-olds were correct more often in congruent than incongruent trials (M = .78 vs. M = .35, Wilcoxon, p = .002, r = .46; M = .94 vs. M = .52, Wilcoxon, p = .002, r = .45, respectively). In addition, we calculated whether 4- and 5-year-olds' choices differed from chance level (.5) in the two congruent as well as in the two in-congruent trials: in congruent trials, 4- and 5-year-olds chose the numerically larger digit significantly more often than would be expected by chance (4-year olds: $t(22) = 4.09$, $p < .001$, d = 1.74; 5-year olds: $t(22) = 12.11$, $p < .001$, d = 5.16). In contrast, in incongruent trials, both age groups were at chance in choosing the numerically larger digit (4-year olds: $t(22) = -1.91$, p = .069, d = -.81; 5-year olds: $t(22) = .214$, p = .83, d = .09).

Comparisons across tasks on group level and individual level — As depicted in Table 2, 4- and 5-year-old children's performance was compared between tasks in which the same range of digits was used: ADGive-N_v, ADGive-N, DNT, DST. The LBT as well as the SCT were not included, because they only involved the digits 2 and 5. We also did not include 6-and 7-year-olds, because of ceiling effects. Comparisons between tasks were made on a group level (comparing group mean values) using Wilcoxon tests as well as on individual level (correlating individual scores) using Kendall's tau-b correlations. Of main interest were the task pairings ADGive-N_v and ADGive-N (cardinality comprehension of number words compared to digits) - as well as DNT, ADGive-N, DST parings (comparing Arabic digit knowledge with regard to digit recognition, cardinality and ordinality comprehension).

A consistent developmental pattern was found on the group level as well as on the individual level. On the group level statistical comparisons revealed the following performance pattern for both age groups: children assigned more cardinal values to number words than to digits (ADGive-N_v > ADGive-N) and they assigned more number words than cardinal values to digits (DNT > ADGive-N). Finally, when children knew the cardinal value of a digit, they also knew its ordinal position (ADGive-N = DST). On the individual level, for all task pairings of interest, performance correlated positively in both age groups: the higher the score in the ADGive-N_v, the higher the score in the ADGive-N. The same positive relation holds for the DNT and the ADGive-N, the DNT and DST as well as the ADGive-N and the DST task pairings.

Table 2

Comparisons Between Tasks on Group Level and Individual Level

Task	DNT		ADGive-N		DST	
Comparison level	4 years	5 years	4 years	5 years	4 years	5 years
ADGive-N_v						
Group	.038	.416	< .001	.041	< .001	.020
Individual	.017 (.41) [7]	.023 (.47) [17]	< .001 (.75) [6]	.004 (.59) [17]	.042 (.38) [6]	.132 (.31) [14]
DNT						
Group			.033	.018	.003	.017
Individual			.001 (.58) [7]	< .001 (.77) [16]	.028 (.39) [7]	.007 (.54) [15]
ADGive-N						
Group					.096	.205
Individual					.014 (.46) [11]	.010 (.5) [15]

Note. Group comparison level: Wilcoxon tests: *p*-values. Individual comparison level: Kendall's Tau-b (τ_b) correlations: *p*-values (τ_b correlation coefficients) [number of ties]. Samples sizes varied between n = 20 and n = 23.

To control for multiple testing, a Fisher's omnibus test was run on the *p*-values of all Wilcoxon tests, which turned out to be significant, $\chi^2(24) = 92.62$, $p < .001$. The Fisher's omnibus test on the *p*-values of all Kendall's Tau-b tests was significant as well, $\chi^2(24) = 113.40$, $p < .001$. Accordingly, a Fisher's omnibus test run on the *p*-values of all Wilcoxon tests and Kendall's Tau-b tests together was significant too, $\chi^2(48) = 206.02$, $p < .001$, indicating that the statistically significant effects reported in Table 2 likely did not result by chance.

Discussion

In this cross-sectional study we documented children's first steps towards learning the relation between Arabic digits and the exact cardinal values they represent. To our knowledge, this is the first study to date which used a broad range of age groups and tasks, including digit recognition, cardinality and ordinality comprehension as well as tasks measuring implicit and explicit access to magnitude information of Arabic digits, to explore and document the developmental trajectory towards Arabic digit knowledge. Of particular interest was the period from preschool to school entry, in which children start to learn about the meaning of Arabic digits. For this purpose the digits in the range of 1 to 6 were chosen for all tasks. A clear pattern emerged across age groups and across tasks with a strong within-child consistency.

First, comparisons across age groups in all tasks revealed a steady growth in proficiency towards learning the cardinal values of Arabic digits. Except in the *line bisection task* (discussed below), 4-year-old children performed worse than 5-year-old children, who performed worse than 6-year-old children. By the age of 6, which demarcates the period of school entry for most children in Germany, children performed as well as 7-year-old children, who already had experienced a year of formal mathematical instruction. That is, both age groups performed at ceiling, showing that they had mastered the Arabic digits up to 6.

Second, in contrast to the results of de Hevia and Spelke (2009) and in line with findings from Hoffmann et al. (2013), by the age of 5 children showed a bisection bias towards the larger digit in the LBT. This suggests that by the age of 5 children access magnitude information of Arabic digits implicitly, at least Arabic digits in the lower number range (2 and 5). Most probably, this was due to children's familiarity with the digits 2 and 5. In contrast to the 4-year-olds, 5-year-old children were sufficiently familiar with the digits 2 and 5 and their meaning, which interfered with their perception of line lengths, leading to a bisection bias towards the larger digit. This bias most likely reflects spontaneous compensation for the perceived magnitude asymmetry of the two task-irrelevant flanker digits (cf. Fischer, 2001). Consistent with this interpretation, the majority of 5-year-olds were able to name the digits 2 and 5 with the correct number word (87%). Likewise, the majority of the 5-year-olds knew the cardinal value of the digits up to 5 or 6 (78%).

The results of the LBT revealed one unexpected exception from the general pattern described above. In contrast to the 5-year-olds, 6-year-old children as a group did not show a bisection bias towards the larger digit in the LBT, only 6-year-old school children showed a marginally significant bias. This finding is inconsistent with the overall developmental trajectory and might therefore represent a random effect occurring in the particular sample tested in this study. However, before we can decide whether this interpretation is correct the result in question needs to be replicated, especially given the possibility that cohort-specific biases may contaminate comparisons in cross-sectional designs.

Third, whereas the LBT measured implicit access to magnitude information of Arabic digits, the ADGive-N task and the SCT measured explicit access to magnitude information of Arabic digits, albeit in different ways. In the ADGive-N task, children were asked to provide the correct amount of nuts in response to a given digit. In the SCT task children were asked to compare the digits 2 and 5 differing not only in numerical but also in physical magnitude. Of the 4-year-olds, only 45% were able to provide the correct amount of nuts in the ADGive-N task for the numbers 2 and 5; consistently, 4-year-olds did not show a bisection bias in the LBT and did not succeed in the SCT, but were at chance in choosing the digit 5 when it was physically smaller than the digit 2. In contrast, 5-year-olds provided the correct amount of nuts for both digits in the ADGive-N task and showed a bisection bias in the LBT but still failed to use their cardinality knowledge in the SCT. Also the 5-year-olds were at chance when the digit 5 was physically smaller than the digit 2, even though they were given as much time as they wanted to compare the digits.

The results of the implicit and explicit measures discussed above fit well with the previous literature on the development of Arabic digit knowledge. Implicit measures of numerical magnitude are thought to be an indicator of automatic access to numerical magnitude. That is, by just seeing an Arabic digit its magnitude representation becomes activated (Girelli et al., 2000). Explicit measures of numerical magnitude commonly reflect intentional processing of numerical magnitude. That is, explicit measures involve processes that are engaged in pursuit of a particular goal (Bugden & Ansari, 2011) and thought to be more effortful (Hoffmann et al., 2013). In line with the recent findings of Hoffmann et al. (2013) the results of the current study indicate that 5-year-old children access magnitude information of Arabic digits in the lower number range implicitly. The observed bisection bias in the LBT shows that 5-year-olds by just seeing the digits processed the digits on a semantic level, despite the fact that the digits were never mentioned to the children and were irrelevant to the task. Five-year-olds also were able to access the magnitude information of the digits explicitly, but only when they were asked for one digit at a time only (ADGive-N task). Interestingly, 5-year-olds failed to access the magnitude information of the same digits in the subsequent SCT. In the SCT children not only had to compare the two digits, they also had to ignore the salient physical size of the digits. This finding parallels the findings of Hoffmann et al. (2013) and show that 5-year-olds are still in the process of elaborating the exact meaning of Arabic digits and that their explicit knowledge of Arabic digits consolidates from 5 to 6 years of age.

Fourth, comparisons of performances between the ADNGive-N task, DNT and the DST of the 4- and 5-year-old children revealed the developmental trajectory preschoolers traverse towards Arabic digit knowledge. The general pattern was the same for 4- and 5-year-old children on a group level as well as on the individual level. As expected, both age groups knew the cardinal values of more number words than of Arabic digits (ADGive-N vs. ADGive-N_v). These behavioral findings are in line with the specific brain activity pattern found by Park et al. (2014) and again suggest that in contrast to the 6-year-olds, the 4- and 5-year-olds were still in the process of strengthening the mapping between Arabic digits and their exact cardinal values. In particular, even though all the 5-year-olds, except for one, were cardinal-principle knowers (they know the cardinal values of the numbers within their verbal count list), they could name more digits than they could provide the cardinal value of. For example, some of the 5-year-olds knew how many items they had to provide when hearing the number word ‘five’, they also could provide the correct number word when presented with the Arabic digit 5, yet they were unable to translate their cardinality knowledge of the number word to the Arabic digit and failed to provide the correct amount of items when presented with the Arabic digit 5.

On the individual level, correlational analyses of DNT, ADGive-N and DST parings revealed significant correlations between all three task pairings, demonstrating a strong within-child consistency in the developmental trajectory towards Arabic digit knowledge: children who recognized more digits also provided more correct cardinal values and ordinal positions of digits. Furthermore, children who were more proficient in cardinality comprehension of digits (ADGive-N task) were also more proficient in ordinality comprehension of digits (DST).

Previous studies (Knudsen, Fischer, & Aschersleben, in press; Sarnecka & Carey, 2008) have shown that children’s comprehension of cardinality of number words in the Give-N task is directly related to their understanding of the ordinal position of number words. Children who know the cardinal value of all the numbers within their counting range (cardinal-principle knowers) also understand the successor function: the word that refers to the cardinality N+1 comes after the word that refers to the cardinality N (as opposed to children who only know the cardinal value of a subset of numbers within their counting range). The non-significant difference in the current study between 4- and 5-year-old’s cardinality comprehension (ADGive-N task) and ordinality comprehension (NST) of digits cannot be clearly interpreted but may suggest that this relation also holds with regard to Arabic digits. Additional evidence comes from the correlational analyses of this task pairing. In both age groups, those children who were more proficient in providing the correct cardinal value were also more efficient in laying out the digits in correct order. Similarly, the relatively high number of ties in this task pairing for about half of the children in each age group indicates that if those children knew the cardinal values of the digits they also knew their ordinal positions. Moreover, children who laid out all digits in the correct order in the DST also, like adults, tended to lay out the digits from left-to-right, rather than from right-to left.

In recent years, the development of symbolic representations of number has been studied intensively. Especially the contribution of non-symbolic and symbolic representations to math achievement at the beginning of formal mathematical education took center stage in many studies (see introduction). From those studies evidence accumulated in favor of the view that the link between non-symbolic and symbolic representations of number becomes weaker between 4 and 6 years of age. That is, non-symbolic and symbolic number representations may overlap considerably less than previously thought. The current study adds to this literature by investigating how children acquire an understanding of the exact meaning of Arabic digits. One might expect that as soon as children develop their first exact symbolic representations of number (cardinality of number words), these representations would translate directly to symbolic representations of a different format (Arabic digits) they can identify. However, the finding that children traverse through a transitional stage in which they cannot produce the correct cardinal value for Arabic digits they do correctly identify, may provide further evidence for children developing a separate exact representational system of symbolic number representations.

Becoming symbol-minded is a crucial developmental task which involves learning about the referential nature of symbolic notations. Children need to learn that symbols, such as Arabic digits, refer to something other than themselves. For example, the Arabic digit '3' is not just two half circles on top of each other, the digit itself carries meaning and refers to the cardinal value of sets. The results of the current study revealed a clear developmental pattern through which preschoolers traverse towards Arabic digit knowledge. Preschoolers traverse from first knowing the cardinal values of number words to name Arabic digits, to knowing their cardinal values and, concurrently, their ordinal position. The main developmental shifts with regard to children’s proficiency to manipulate magnitude information of Arabic digits occur between 4 and 6 years of age. By the age of 5, children access magnitude information of digits implicitly as well as explicitly, but their explicit knowledge of magnitude of digits consolidates by 6 years of age. This improvement of explicit cardinality knowledge of digits is accompanied by an improvement in translating cardinality knowledge of number words to digits. By the age of 6, which for most children in Germany demarcates the period of school entry, children are as proficient as 7-year-old school children in manipulating magnitude information of Arabic digits.

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Competing Interests

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References

Bartelet, D., Vaessen, A., Blomert, L., & Ansari, D. (2014). What basic number processing measures in kindergarten explain unique variability in first-grade arithmetic proficiency? *Journal of Experimental Child Psychology, 117*, 12-28. doi:10.1016/j.jecp.2013.08.010

Benoit, L., Lehalle, H., Molina, M., Tijus, C., & Jouen, F. (2013). Young children's mapping between arrays, number words, and digits. *Cognition, 129*, 95-101. doi:10.1016/j.cognition.2013.06.005

Bugden, S., & Ansari, D. (2011). Individual differences in children's mathematical competence are related to the intentional but not automatic processing of numerals. *Cognition, 118*, 32-44. doi:10.1016/j.cognition.2010.09.005

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition, 44*, 1-42. doi:10.1016/0010-0277(92)90049-N

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General, 122*, 371-396. doi:10.1037/0096-3445.122.3.371

de Hevia, M. D., & Spelke, E. S. (2009). Spontaneous mapping of number and space in adults and young children. *Cognition, 110*, 198-207. doi:10.1016/j.cognition.2008.11.003

de Hevia, M. D., Vallar, G., & Girelli, L. (2008). Visualizing numbers in the mind's eye: The role of visuo-spatial processes in numerical abilities. *Neuroscience & Biobehavioral Reviews, 32*, 1361-1372. doi:10.1016/j.neubiorev.2008.05.015

DeLoache, J. S. (2002). The symbol-mindedness of young children. In W. Hartup & R. A. Weinberg (Eds.), *Child psychology in retrospect and prospect: Celebration of the 75th anniversary of the Institute of Child Development* (Vol. 32, pp. 73-101). Mahwah, NJ: Lawrence Erlbaum.

De Smedt, B., Noël, M.-P., Gilmore, C., & Ansari, D. (2013). How do symbolic and non-symbolic numerical magnitude processing skills relate to individual differences in children's mathematical skills? A review of evidence from brain and behavior. *Trends in Neuroscience and Education, 2*, 48-55. doi:10.1016/j.tine.2013.06.001

Feigenson, L., Dehaene, S., & Spelke, E. S. (2004). Core systems of number. *Trends in Cognitive Sciences, 8*, 307-314. doi:10.1016/j.tics.2004.05.002

Fischer, M. H. (2001). Number processing induces spatial performance biases. *Neurology, 57*, 822-826. doi:10.1212/WNL.57.5.822

Gebuis, T., Kadosh, R. C., de Haan, E., & Henik, A. (2009). Automatic quantity processing in 5-year-olds and adults. *Cognitive Processing, 10*, 133-142. doi:10.1007/s10339-008-0219-x

Girelli, L., Lucangeli, D., & Butterworth, B. (2000). The development of automaticity in accessing number magnitude. *Journal of Experimental Child Psychology, 76*, 104-122. doi:10.1006/jecp.2000.2564

Göbel, S. M., Watson, S. E., Lervåg, A., & Hulme, C. (2014). Children's arithmetic development: It is number knowledge, not the approximate number sense, that counts. *Psychological Science, 25*, 789-798. doi:10.1177/0956797613516471

Hoffmann, D., Hornung, C., Martin, R., & Schiltz, C. (2013). Developing number–space associations: SNARC effects using a color discrimination task in 5-year-olds. *Journal of Experimental Child Psychology, 116*, 775-791. doi:10.1016/j.jecp.2013.07.013

Holloway, I. D., & Ansari, D. (2009). Mapping numerical magnitudes onto symbols: The numerical distance effect and individual differences in children's mathematics achievement. *Journal of Experimental Child Psychology, 103*, 17-29. doi:10.1016/j.jecp.2008.04.001

Jewell, G., & McCourt, M. E. (2000). Pseudoneglect: A review and meta-analysis of performance factors in line bisection tasks. *Neuropsychologia, 38*, 93-110. doi:10.1016/S0028-3932(99)00045-7

Knudsen, B., Fischer, M. H., & Aschersleben, G. (in press). Development of spatial preferences for counting and picture naming. *Psychological Research*.

Lyons, I. M., Ansari, D., & Beilock, S. L. (2012). Symbolic estrangement: Evidence against a strong association between numerical symbols and the quantities they represent. *Journal of Experimental Psychology: General, 141*, 635-641. doi:10.1037/a0027248

Moyer, R. S., & Landauer, T. K. (1967). Time required for judgments of numerical inequality. *Nature, 215*, 1519-1520. doi:10.1038/2151519a0

Mussolin, C., Nys, J., Content, A., & Leybaert, J. (2014). Symbolic number abilities predict later approximate number system acuity in preschool children. *PLOS ONE, 9*, Article e91839. doi:10.1371/journal.pone.0091839

Park, J., Li, R., & Brannon, E. M. (2014). Neural connectivity patterns underlying symbolic number processing indicate mathematical achievement in children. *Developmental Science, 17*, 187-202. doi:10.1111/desc.12114

Rubinsten, O., Henik, A., Berger, A., & Shahar-Shalev, S. (2002). The development of internal representations of magnitude and their association with Arabic numerals. *Journal of Experimental Child Psychology, 81*, 74-92. doi:10.1006/jecp.2001.2645

Sarnecka, B. W., & Carey, S. (2008). How counting represents number: What children must learn and when they learn it. *Cognition, 108*, 662-674. doi:10.1016/j.cognition.2008.05.007

Sasanguie, D., De Smedt, B., Defever, E., & Reynvoet, B. (2012). Association between basic numerical abilities and mathematics achievement. *The British Journal of Developmental Psychology, 30*, 344-357. doi:10.1111/j.2044-835X.2011.02048.x

Sasanguie, D., Van den Bussche, E., & Reynvoet, B. (2012). Predictors for mathematics achievement? Evidence from a longitudinal study. *Mind, Brain, and Education, 6*, 119-128. doi:10.1111/j.1751-228X.2012.01147.x

Shaki, S., Fischer, M. H., & Göbel, S. M. (2012). Direction counts: A comparative study of spatially directional counting biases in cultures with different reading directions. *Journal of Experimental Child Psychology, 112*, 275-281. doi:10.1016/j.jecp.2011.12.005

Tversky, B., Kugelmass, S., & Winter, A. (1991). Cross-cultural and developmental trends in graphic productions. *Cognitive Psychology, 23*, 515-557. doi:10.1016/0010-0285(91)90005-9

Vogel, S. E., Remark, A., & Ansari, D. (2015). Differential processing of symbolic numerical magnitude and order in first-grade children. *Journal of Experimental Child Psychology, 129*, 26-39. doi:10.1016/j.jecp.2014.07.010

Whyte, J. C., & Bull, R. (2008). Number games, magnitude representation, and basic number skills in preschoolers. *Developmental Psychology, 44*, 588-596. doi:10.1037/0012-1649.44.2.588

Wynn, K. (1990). Children's understanding of counting. *Cognition, 36*, 155-193. doi:10.1016/0010-0277(90)90003-3

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