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RESEARCH ARTICLE

Mapping skills between symbols and quantities in preschoolers: The role of finger patterns

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Abstract

Mapping skills between different codes to represent numerical information, such as number symbols (i.e., verbal number words and written digits) and non-symbolic quantities, are important in the development of the concept of number. The aim of the current study is to investigate children's mapping skills by incorporating another numerical code that emerges at early stages in development, finger patterns. Specifically, the study investigates (i) the order in which mapping skills develop and the association with young children's understanding of cardinality; and (ii) whether finger patterns are processed similarly to symbolic codes or rather as non-symbolic quantities. Preschool children (3-year-olds, $N = 113$, $M_{age} = 40.8$ months, $SD_{age} = 3.6$ months; 4-year-olds, $N = 103$, $M_{age} = 52.9$ months, $SD_{age} = 3.4$ months) both cardinality knowers and subset-knowers, were presented with twelve tasks that assessed the mappings between number words, Arabic digits, finger patterns, and quantities. The results showed that children's ability to map symbolic numbers precedes the understanding that such symbols reflect quantities, and that children recognize finger patterns above their cardinality knowledge, suggesting that finger patterns are symbolic in essence.

KEYWORDS
cardinality, early numeracy, finger patterns, mapping skills, preschool children

Research Highlights

- Children are more accurate in mapping between finger patterns and symbols (number words and Arabic digits) than in mapping finger patterns and quantities, indicating that fingers are processed holistically as symbolic codes.
- Children can map finger patterns to symbols above their corresponding cardinality level even in subset-knowers.
- Finger patterns may play a role in the process by which children learn to map symbols to quantities.
- Fingers patterns' use in the classroom context may be an adequate instructional and diagnostic tool.

1 | INTRODUCTION

Mapping or the ability to effectively transcode between different numerical representations, such as symbolic numbers and quantities, has been identified as an important indicator of the child's early mathematical learning and development (Purpura et al., 2013). Prior research has largely focused on mappings between verbal number words, written digits, and non-symbolic quantities such as dot arrays. Less is known about other types of numerical representation that constitute the first instance of young children's communication about quantities—finger patterns. Indeed, it has been suggested that fingers might play a facilitating role during the process of associating symbols with the quantity that they represent (Butterworth, 1999; Fayol & Seron, 2005; Roesch & Moeller, 2015). In the present study, we aim to provide a comprehensive view of how mapping abilities in young children develop. To this end, we focus on 3-to-4-year-olds—this corresponds to a developmental stage in which children start grasping the understanding of cardinality or how symbol numbers relate to quantities.

1.1 | Mapping between number words, Arabic digits, and quantities

Numerical information can be conveyed through different external representations or codes. According to the influential triple-code model (Dehaene, 1992), there are three representational codes for numerical information: the visual Arabic number form (e.g., "3"), the auditory-verbal word frame (e.g., "three"), and analog non-symbolic quantity representations (e.g., •••). An important milestone in young children's mathematical development is to learn the mappings between these representational codes. For instance, research has shown that children's skills in mapping between different representations of numbers are related to their early arithmetic performance (e.g., Brankaer et al., 2014; Defever et al., 2013; Guo et al., 2021; Malone et al., 2019; Mundy & Gilmore, 2009; Purpura et al., 2013; Short & McLean, 2023).

Despite the relevance of mapping skills in the development of the concept of number—mapping activities feature in many early childhood education (ECE) curriculums worldwide and ECE practitioners are typically encouraged to support young children's mapping skills (Merkley & Ansari, 2016)—few studies have directly analyzed young children's mapping skills during the preschool years and the order in which these mappings between different numerical representations are acquired (Benoit et al., 2013; Hurst et al., 2017; Jiménez Lira et al., 2017; Marinova et al., 2021). Benoit et al. (2013) assessed 3, 4, and 5-year-olds' mapping skills (n = 144) between number words, written digits, and non-symbolic quantities with small (1–3) and large numbers (4–6). Their central question was whether children would acquire the mappings between quantities and Arabic digits before or after the mappings between number words and Arabic digits or quantities. Results showed that children learn to map quantities to number words and quantities to Arabic digits before they can directly connect number words to Arabic digits. According to the authors, the non-symbolic code based on quantities may have a privileged status and serve as a foundation in the acquisition of the symbolic codes, initially number words and later Arabic digits. Finally, children map number words to Arabic digits.

However, later studies have found different results compared to those of Benoit and colleagues (Hurst et al., 2017; Jiménez Lira et al., 2017; Marinova et al., 2021). In these studies, children performed worse on mappings between quantities and Arabic digits. Indeed, these studies support the idea that the mappings between quantities and Arabic digits are only acquired once the mappings between quantities and number words and between number words and Arabic digits have been acquired (see also Bialystok, 1992). One possible explanation for these discrepancies is that in Benoit et al.'s study, quantities (arrays of dots) were arranged in familiar patterns like those used on dice, whereas later studies presented quantities using random configurations. In this way, children in Benoit et al.'s study probably recognized specific dice patterns, which might have improved performance on mappings involving quantities.

There is also some discrepancy regarding the order of acquisition of number words-quantities and number words-Arabic digits mappings. Research suggests that children develop the links between number words and quantities before they map Arabic digits to the corresponding number words. Children can recognize and discriminate non-symbolic quantities from an early age. Number words are the first symbols that young children learn (Le Corre & Carey, 2007). Around the age of two, most children can recite some number words in order, and at the same time, they learn to form direct mappings between individual number words and non-symbolic magnitudes (Le Corre & Carey, 2007; Le Corre et al., 2006; Lipton & Spelke, 2005; Wynn, 1990, 1992). Nevertheless, learning these mappings is a difficult and protracted process, as shown by studies that have analyzed the acquisition of cardinality (Sarnecka & Lee, 2009; Wynn, 1990, 1992). According to these studies, children do not grasp an understanding of cardinality for all the number words simultaneously. This is a sequential process that involves different stages. This progression is illustrated in the Give-a-number task (Sarnecka & Carey, 2008; Wynn, 1990), in which children are tasked to produce a particular number of tokens. Initially, children give one token when asked for one but give a random number of tokens when asked for any other number. These children are called one-knowers (Le Corre & Carey, 2007). Similar patterns are found for two-knowers, three-knowers, and four-knowers. They accurately produce up to two, three, and four tokens, respectively. These stages are also referred to as "subset-knowing." It is only after children become four-knowers that they successfully generalize that knowledge to larger sets. These children are referred to as cardinality principle knowers or CP-knowers (e.g., Le Corre & Carey, 2007; Sarnecka & Lee, 2009).

In this context, Jiménez Lira et al. (2017) hypothesized that children first acquire the mappings between quantities and number words but only for small quantities (#1–3). Mappings between larger quantities and number words would take longer to master because these mappings require children to develop an understanding of cardinality and counting strategies (e.g., one-to-one correspondence) to determine the quantity. According to these authors, children would develop mappings between number words and Arabic digits more quickly than mappings between number words and large quantities because the former only require that children assign spoken number words to written digits without understanding the quantities involved. Their results with 3 and 4-year-olds ($n = 62$) were in line with these predictions. Similarly, Hurst et al. (2017), with a sample of 3 and 4-year-olds ($n = 48$), found that, unlike mappings involving quantities (i.e., number words-quantities and Arabic digits-quantities), the mapping between number words and Arabic digits was independent of the magnitude of the quantities the symbols represent, suggesting that number words and Arabic digits are directly mapped to each other without reference to the quantity those symbols represent. In a later study, Marinova et al. (2021) observed that 3, 4, and 5-year-olds ($n = 193$) performed worse on Arabic digits-quantities mapping compared to the performance of the children in the studies by Jimenez Lira et al. (2017) and Hurst et al. (2017) on the same task. Marinova and colleagues speculated that the children in their study could have insufficient knowledge of Arabic numerals at the time of testing, leading to an overall worse performance in mappings involving these symbols.

These discrepancies between extant studies suggest that incidental or explicit experiences with numerical representations during the early years shape the mapping skills that can be observed or the order in which the various mappings are acquired. In other words, the order of acquisition of different mappings, especially whether the pure symbolic mapping precedes mapping symbol numbers onto quantity representations, likely depends on the child's understanding of cardinality. However, previous studies have not considered this possibility, which is particularly surprising given that mapping skills depend on children's ability to establish the numerosity of sets, especially mappings involving quantities (e.g., Gunderson et al., 2015b; Sokolowski et al., 2022). Accordingly, in the present study, we explored children's mapping skills by considering their level of cardinality as assessed through the Give-a-number task. Furthermore, we incorporated one more representational code for numerical information, finger patterns, to analyze its associations with the other codes described above.

1.2 | Finger patterns and numbers

Another representational code, canonical finger patterns (e.g., holding up index, middle, and ring fingers to indicate "three"), could potentially play a functional role in young children's understanding of the concept of number and the ability to map between symbolic numbers and quantities (Butterworth, 1999; Di Luca & Pesenti, 2011; Gibson et al., 2019). Children can use their fingers to communicate numerical information even before having acquired number words or Arabic digits (Fuson, 1988). For instance, Gunderson et al. (2015a) found that young children were more than twice as accurate when labeling small sets of objects (2–3) with finger patterns than with words and that they were able to label sets (using fingers) above their cardinality knowledge (see also Orrantia et al., 2022). This representational code based on fingers may be considered as an addition to the triple-code model (Orrantia et al., 2022; Sixtus et al., 2023) and therefore be susceptible to mappings with the other codes.

Finger patterns share commonalities with both the non-symbolic code (i.e., quantity) and symbolic codes (i.e., number words and Arabic digits; Di Luca & Pesenti, 2011; Wiese, 2007). Like non-symbolic quantities, finger patterns have iconic properties that preserve their cardinal value (a finger pattern is directly related to the number of items the pattern is meant to describe). Like symbolic codes, finger patterns can serve as summary symbols to represent a specific quantity of items and communicate the cardinal value of a set (Gunderson et al., 2015a, 2015b). In this sense, the extent to which finger patterns are processed similarly to non-symbolic or symbolic codes in mapping tasks is an open question.

Several studies have suggested that canonical finger patterns have a special status as learned patterns stored in long-term memory, supporting the idea that finger patterns provide automatic access to number semantics, just like Arabic digits. For instance, some studies that have contrasted performance in canonical versus non-canonical finger pattern recognition, have found that canonical finger patterns are named faster compared to non-canonical ones in adults (Barrocas et al., 2020; Di Luca et al., 2010; Di Luca & Pesenti, 2008; Soylu et al., 2019; Van den Berg et al., 2021, 2022). There is also evidence that canonical finger patterns afford faster access to number semantics than non-canonical finger patterns in kindergarten and elementary school children (Kreilinger et al., 2021; Lafay et al., 2013; Marlair et al., 2021; Nöel, 2005), although the results with younger children are mixed. For instance, in a cross-sectional study conducted by Lafay et al. (2013), 4–7-year-old children performed finger pattern comparison and identification tasks using both canonical and non-canonical patterns. Their results showed that, regardless of their age, children were sensitive to the canonicity of finger patterns in the comparison task, which only requires simple pattern processing. However, in the finger pattern recognition task, which requires not only processing the patterns but also recognizing and labeling them, the canonicity advantage was not observed for the youngest children, suggesting that in this age group, children do not yet map between canonical finger patterns and number words.

Research regarding younger children, that is, children who are still in the process of learning the cardinal meanings of numbers, is scarce. To the best of our knowledge, only one study has investigated whether children below the age of four understand canonical finger patterns as non-symbolic sets of items or rather view these patterns as whole gestalts, akin to symbolic codes. Gibson et al. (2022) compared children's ability to enumerate finger patterns to their ability to enumerate non-symbolic sets (arrays of shapes). Results showed an overall advantage of labeling finger patterns over dot arrays, even when children are subset-knowers, which would suggest that young children view finger patterns as number symbols. Because children were more proficient at mapping number words to finger patterns than to non-symbolic sets, Gibson et al. (2022) suggested the possibility that finger patterns could act as a bridge between number symbols and the quantities they represent.

Taken together, the results of these studies suggest that finger patterns could be processed as symbolic codes that can be recognized holistically, although results with younger children are mixed. Furthermore, these studies have primarily focused on mapping from finger patterns to number words. it is unknown whether mappings between finger patterns and other representational codes of numbers are observed in young children.

1.3 | The current study

The current study aims to broaden our understanding of children's mapping skills across number representations by incorporating finger patterns. To the best of our knowledge, no studies have investigated all four codes using a single paradigm. To achieve this, we present 3- and 4-year-old children with twelve tasks that assess the mappings between quantities, number words, Arabic digits, and finger patterns for numbers ranging from 2 to 7 in both directions of each mapping (e.g., from quantities to finger patterns and finger patterns to quantities).

We address two main research questions in this study. The first question pertains to the order in which children acquire the mappings among the four codes and whether this acquisition depends on the children's level of cardinality. Based on previous studies, we expect that children would first start mapping number words to quantities and simultaneously acquire mappings between Arabic numerals and number words, although this may depend on the size of the numbers. Only after acquiring these mappings, we hypothesize that children would start mapping Arabic digits to quantities. Our second research question relates to mappings with finger patterns. If finger patterns are processed like symbolic codes, as suggested by previous research, we expect children to begin mapping finger patterns onto symbolic codes (number words and Arabic digits). However, it is also possible that younger children have not yet developed holistic representations of finger patterns and instead process them as non-symbolic quantities. In this case, mappings between symbolic codes and finger patterns would be acquired later.

Regarding children's level of cardinality, there are no reasons to expect young children to perform all mappings based on their level of cardinality. As argued by Hurst et al. (2017) and Jimenez Lira et al. (2017), mappings between Arabic numerals and number words can be learned through rote association without reference to the quantities they represent. These mappings would not depend on understanding the meanings of symbols and, therefore, would not be influenced by children's knowledge of cardinality. On the other hand, mappings involving quantities are conditioned by children's ability to establish the numerosity of sets. Hence, we expect that children's performance on these mappings would align with their level of cardinality. In a similar line of argument, if finger patterns are processed as symbols, the mappings between finger patterns and other symbolic codes (number words and Arabic digits) would not depend on the level of cardinality.

2 | METHOD

2.1 | Participants

We recruited 216 children from two public schools in a middle socioeconomic status area of a midsize city in Spain[1]. The children were divided into two age groups: 113 3-year-olds (M_{age} = 40.8 months, SD = 3.6 months, 56% female) and 103 4-year-olds (M_{age} = 52.9 months, SD = 3.4 months, 52% female). Parental consent was obtained for all children, and the experimental procedures were approved by the Human Experimentation Ethics Committee of the university of the first author.

2.2 | Measures

2.2.1 | Mapping tasks

Children completed twelve mapping tasks that involved four types of stimuli for numbers 1–7. The stimuli included (see Figure S1):

a. Quantities: Colored dots (green, blue, orange, or black) placed within white squares (7.7 cm × 7.7 cm). The size of the dots in a set varied, and the configuration of the set changed on each trial.
b. Number words: The seven number words were provided verbally by a native Spanish-speaking research assistant.
c. Arabic digits: Black font numerals placed within white squares (7.7 cm × 7.7 cm).
d. Finger patterns: Photographs taken with a digital camera showing the palm of the right hand for numbers 1–5 and both hands for numbers 6–7. The pictures included canonical finger patterns typically used by Spanish children to refer to numbers, such as raising the index finger for one, using the index finger and the middle finger for two, and continuing with the natural order of fingers for larger numbers (Sánchez et al., 2024).

In each task, children had to choose which of three stimuli matched a target stimulus. For all tasks (except those involving number words), children were presented with a card containing the target number (dots/Arabic digits/finger patterns) with magnitudes from two to seven. They were tasked to choose among three stimuli involving the target number and adjacent numbers. For example, in mappings between quantities and Arabic digits, if children were presented with a card with three dots, they had to choose the corresponding Arabic numeral among numerals 2, 3, or 4. The tasks involving number words were similar, except that the target number word and the choices of number words were provided verbally by the experimenter. To reduce demands on working memory, the number words were repeated twice.

The twelve mapping tasks were presented in separate booklets, and the order of the booklets was counterbalanced across participants. Each mapping task began with a single practice trial using the target number 1 and response options 1, 2, and 3. Next, experimental trials were administered in a pseudorandom order within set size groups: small (2–3), medium (4–5), and large (6–7). Counting was not encouraged but allowed if the child wished to do so. The experimenter coded whether children counted in tasks involving quantities and finger patterns. Children received 1 point for a correct match between the target and response option and 0 points for an incorrect response, no response, or other reasons. All task-specific reliability coefficients (Cronbach's alpha) exceeded 0.70. Coefficients for combined tasks (not taking into account directionality of mapping; see preliminary and main analyses below) exceeded 0.80. Task-specific and combined coefficients are reported in Table S1.

2.2.2 | Give-a-number task

In this task (see Le Corre & Carey, 2007; Wynn, 1992), a set of 15 small balls (3 cm in diameter) was given to participants, and a plastic animal (a bear) was placed in front of them. Children were asked to give the bear exactly *N* balls, beginning with one ball. Once they gave the bear *N* balls, they were asked, "Is that *N*?" If the child agreed, then the next trial began. If the child disagreed, then the experimenter prompted the child to give the correct amount by saying, "But the bear wanted *N* balls, could you give the bear *N* balls?" If the child succeeded at giving a number *N*, they were asked to give the next consecutive number ($N + 1$), with 10 being the highest number requested. If the child failed to give N, the next request was for $N - 1$. The highest number of objects that children accurately gave the experimenter on at least two of three attempts was coded as their number-knower level. Cronbach's alpha reliability coefficient was 0.90.

2.3 | Procedure

Children were tested individually by trained research assistants in their respective schools in a separate and quiet room. The total duration of the individual testing was about 40 min per child, divided into two sessions no longer than 1 week apart. Testing took place during the first semester of the academic year (October and November).

2.4 | Analytical approach

To investigate the aims of the current study, first, we focused on how mapping abilities in young children varied as a function of the type of mapping (*task*), number size (*number*), and cardinality knowledge (*cardinality*). To this end, we used a mixed model. This analytical approach takes into account that the data had a hierarchical structure and reduces the likelihood of Type I error substantially. For instance, this approach is more appropriate than simply aggregating data at the person or item levels to investigate "task effects" (for instance, how mapping abilities vary as a function of number size and mapping task). Thus, we specified a generalized mixed model with probit link in which the probability that a trial was correctly endorsed (coded as 1; i.e., probability above 0.5 indicates success) was a function of *cardinality*, *number*, and *task*. We also included age as a covariate in the model. Besides the main effects, we included in the model all 2- and 3-way interactions (except those involving the covariate).

Before addressing the substantive questions in the current study, we first ran a preliminary analysis (generalized mixed model) to investigate whether the sequence of presentation or directionality affected performance in each task and group (see Table S3).

All descriptive analyses and generalized mixed models were estimated using GAMLj in Jamovi (Version 2.2.5). Unless otherwise indicated, the Bobyqa optimizer was used in analyses. The proportions of reduced error (pseudo R2) are reported as R2 Marginal (R2M, the variance explained by the fixed effects over the total variance of the dependent variable) and R2 Conditional (R2C, the variance explained by the fixed and the random effects together over the total variance of the dependent variable). Initially, we specified a baseline model (unconditional) with random intercepts at the item and person level to determine the corresponding intraclass correlation coefficient (ICC). From a statistical perspective, ICCs lower than 0.10 suggest small cluster effects and may cause estimation difficulties (e.g., Brunner et al., 2017). Then, we included fixed effects and interactions and determined the random structure—starting with the maximal random effects structure justified by the design as recommended by Barr et al. (2013). We selected the best structure based on statistical grounds (model fit indices, AIC and BIC; smaller values suggest a better model). Factors (*cardinality*, *number*, and *task*) were effect coded, and we used simple contrasts to estimate the corresponding parameter estimates.

3 | RESULTS

Descriptive statistics (subject-level) and age-adjusted bi-variate correlations are shown in Table 1 (accuracies per grade, task, and number size are shown in Table S2).

3.1 | Development of mapping abilities in young children

Table 2 shows the results of the omnibus tests. The marginal and conditional R^2 were 0.45 and 0.65, respectively. Model fitting and parameter estimates can be found in Table S4.

All main effects were statistically significant. Older children showed better mapping abilities. Mapping large numbers was more error-prone than mapping small numbers (see model-implied probabilities in Figure 1, top right panel). For instance, whereas the probability of successfully mapping #2 was 0.92 (95% CI 0.89–0.94), the corresponding probability for #7 was 0.24 (95% CI 0.20–0.28). The analysis also revealed that children were more efficient with *pure* symbolic mappings (Digit-Word). Indeed, the probability of success for mappings that involved quantities was below 0.5 (see model-implied probabilities in Figure 1, top left panel). Cardinality knowers were more proficient than non-cardinality knowers (contrasts can be found in Table S4).

TABLE 1 Descriptive statistics (top panel) and age-adjusted bi-variate correlations (bottom panel).

Task	Mean	SD	Minimum	Maximum	Skewness	Kurtosis
1. Give_n#	3.82	1.29	1	5	−0.61	−1.01
2. DgW	0.77	0.30	0	1	−1.17	0.11
3. WFin	0.66	0.27	0	1	−0.58	−0.50
4. DgFin	0.63	0.30	0	1	−0.57	−0.71
5. WDot	0.54	0.25	0	1	−0.24	−0.66
6. FinDot	0.52	0.25	0	1	−0.13	−0.64
7. DgDot	0.50	0.27	0	1	−0.05	−0.99

	1	2	3	4	5	6
2. DgW	0.493***					
3. WFin	0.566***	0.592***				
4. DgFin	0.483***	0.581***	0.703***			
5. WDot	0.412***	0.491***	0.624***	0.588***		
6. FinDot	0.437***	0.417***	0.521***	0.522***	0.549***	
7. DgDot	0.456***	0.437***	0.562***	0.575***	0.582***	0.565***

***$p < 0.001$; #recoded (< 2 = 1 and > 4 = 5); Give-n (Give-a-number task), DgW (Arabic digits and number words), DgFin (Arabic digits and finger patterns), WFin (number words and finger patterns), FinDot (finger patterns and dot array), DgDot (Arabic digits and dot array), WDot (dot array and number words).

TABLE 2 Main and interaction effects of the model predicting mapping skills.

	X^2	Df	*p*
Number	1206.7	5	<0.001
Task	335.6	5	<0.001
Age	21.4	1	<0.001
Give_m	113.6	4	<0.001
Number * Task	94.9	25	<0.001
Number * Give_n	140.6	20	<0.001
Task * Give_n	94.7	20	<0.001
Number * Task * Give_n	117.9	100	0.106

The interaction between *task* and *number* was significant. Figure 1 (bottom left panel) shows that differences in the probability of a correct response between tasks varied as a function of number size. For large numbers (#6 and #7), only performance on *pure* symbolic mappings revealed probabilities above 0.5. It can also be observed that children were more effective at mapping finger patterns with symbolic numbers than with quantities (i.e., the range included numbers #4 and #5). All two-way interactions with cardinality knowledge were significant. For instance, whereas the probability of a correct response for cardinality knowers was above 0.5 for numbers up to #6, the corresponding probability for 2- and 3-knowers was above 0.5 only for numbers up to #3. Similarly, whereas the probability of a correct response for cardinality knowers was above 0.5 across all mapping tasks, the corresponding probability of a correct response for 1- and 2-knowers was above 0.5 only in the pure symbolic mapping task. This suggests that cardinality affects the order in which mapping skills emerge (see Figure 1, bottom right panel).

Although the three-way interaction did not reach the standard levels of significance—that is, across all cardinality levels performance decreased as a function of number size and children performed better on the pure symbolic mapping—there were indeed differences across cardinality level groups in the pattern that emerges of the interaction between number and task (see Figure 2; omnibus tests can be found in Table S5). For cardinality knowers (Figure 2, bottom right) the interaction between *task* and *number* is clearer and three different trajectories can be distinguished—corresponding to *pure* symbolic mapping, mapping between symbolic numbers and finger patterns, and finally, mapping quantities onto symbolic numbers and finger patterns. Indeed, only mappings that did not involve quantities showed a probability of a correct response above 0.5 for all numbers that were tested (#2-to-#7). For small numbers (#2 and #3) no differences were found across mapping tasks. Notably, the likelihood of a correct response for these children was below 0.5 for mappings involving quantities and large numbers (#6 and #7). The probability of a correct response for four-knowers (Figure 2, bottom left) was also above 0.5 for pure symbolic mappings. However, when finger patterns and symbolic numbers were involved, the corresponding probability was above 0.5 only for patterns up to number #5. The probability of a correct response on mappings that included quantities was below 0.5 for numbers #4 and above. Three-knowers (Figure 2, top right) also showed a similar pattern to that of 4-knowers regarding mappings that included finger and symbolic numbers and mappings that included quantities. However, the probability of a correct response for these children was below 0.5 for pure symbolic mappings that included large numbers (#6 and #7). Regarding 2-knowers in the current study (Figure 2, top left), they only showed knowledge of symbolic numbers (pure symbolic mapping) and mapping between symbolic numbers and finger patterns up to #3. When mapping involved quantities, children's performance aligned with their cardinality level.

4 | DISCUSSION

The present study investigated mapping skills in 3- and 4-year-old children—or their ability to efficiently transcode across different representations of numerical magnitude. Specifically, we focused on (i) the order in which mapping skills developed and the association with young children's understanding of cardinality, and (ii) whether finger patterns were processed similarly to symbolic codes or rather as non-symbolic quantities. Our findings revealed several key results. First, children's ability to map symbolic numbers precedes their understanding that such symbols reflect quantities—even for small numbers. Second, mapping between symbolic numbers and quantities largely aligns with the child's cardinality level—there was very limited evidence that number words are mapped onto quantities before digits are. Third, children recognize finger patterns above their cardinality knowledge level—hence, suggesting that finger patterns are symbolic in essence.

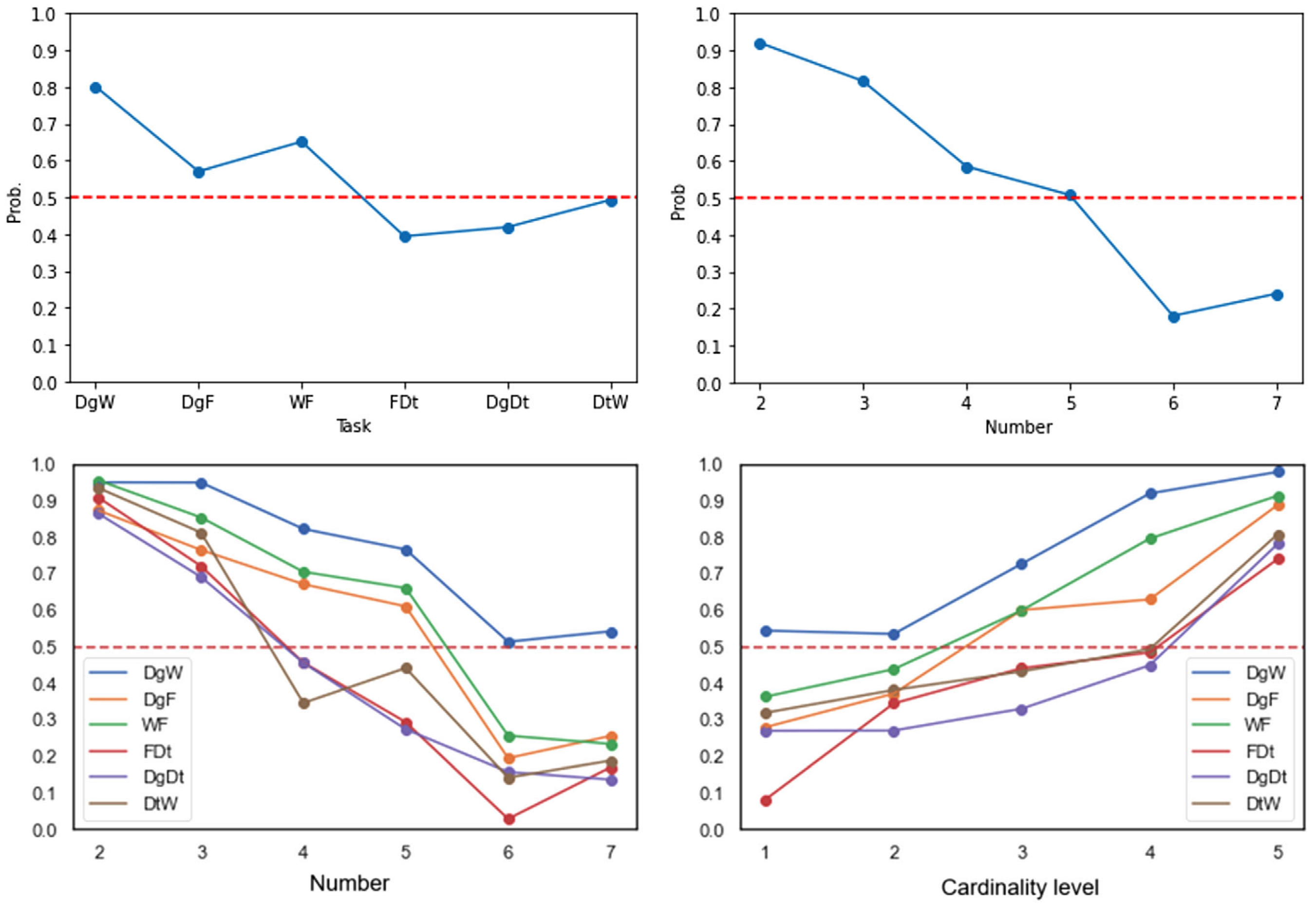

FIGURE 1 Estimated probabilities (y axis) for *number* and *task* effects (top panels) and interactions *task***number* and *cardinality***task* (bottom panels). *Note*: DgW (Arabic digits and number words), DgFin (Arabic digits and finger patterns), WFin (number words and finger patterns), FinDot (finger patterns and dot array), DgDot (Arabic digits and dot array), WDot (dot array and number words). Cardinality levels 1-to-4 relate to subset-knowers.

To compare our results with previous studies, we focus on the three types of representations that have been investigated so far. Our findings revealed that, young children's ability to map across symbolic representations of number precedes that related to non-symbolic quantities. This supports the idea put forth by Jimenez Lira et al. (2017) that children acquire mappings between number words and digits more rapidly than mappings involving quantities. The former may rely on rote association of symbols, while the latter requires the development of counting strategies to determine the quantity, which is a more complex and time-consuming process that usually takes place over a time of months (Sarnecka & Lee, 2009; Wynn, 1990, 1992). Further support for this possibility comes from the results of our study considering the levels of cardinality. This analysis showed that children were able to map number words and digits beyond their cardinality levels. Indeed, even 2-knowers were able to map number words and digits up to #4, hence suggesting a clear dissociation between semantic properties and orthographic/phonological properties of symbolic numbers.

It is worth mentioning that, in contrast to our predictions, we did not find clear evidence that mappings involving quantities aligned with the child's cardinality level. For instance, four-knowers were not able to correctly map four dots and the corresponding symbolic representation. Similarly, cardinality knowers were more error prone when presented with mappings involving quantities corresponding to large numbers (i.e., #6 and #7) than with numbers smaller than #6. These findings are consistent with a recent study suggesting that preschoolers' number knowledge relates to processing quantities within their knower-level, but only for quantities smaller than four (Sokolowski et al., 2022). According to Sokolowski and colleagues, young children may be using two different systems depending on the size of the quantities to be processed: an approximate number system (ANS) to process large quantities (>4), which renders an approximate response, and a parallel individuation system (PI system) to process small quantities (<~4, also termed "subitizing"; see Feigenson et al., 2004, and Hyde, 2011, for a review of these systems). Subitizing renders an exact response and would not rely on mastering the counting principles. In the current study, we speculate that, for mappings involving quantities, children process small quantities using the PI system within their knower level. For instance, two-knowers would be more accurate at mapping between quantities and symbols corresponding to numbers #1 and #2 than to #3. Similarly, for four-knowers, the odds of a correct

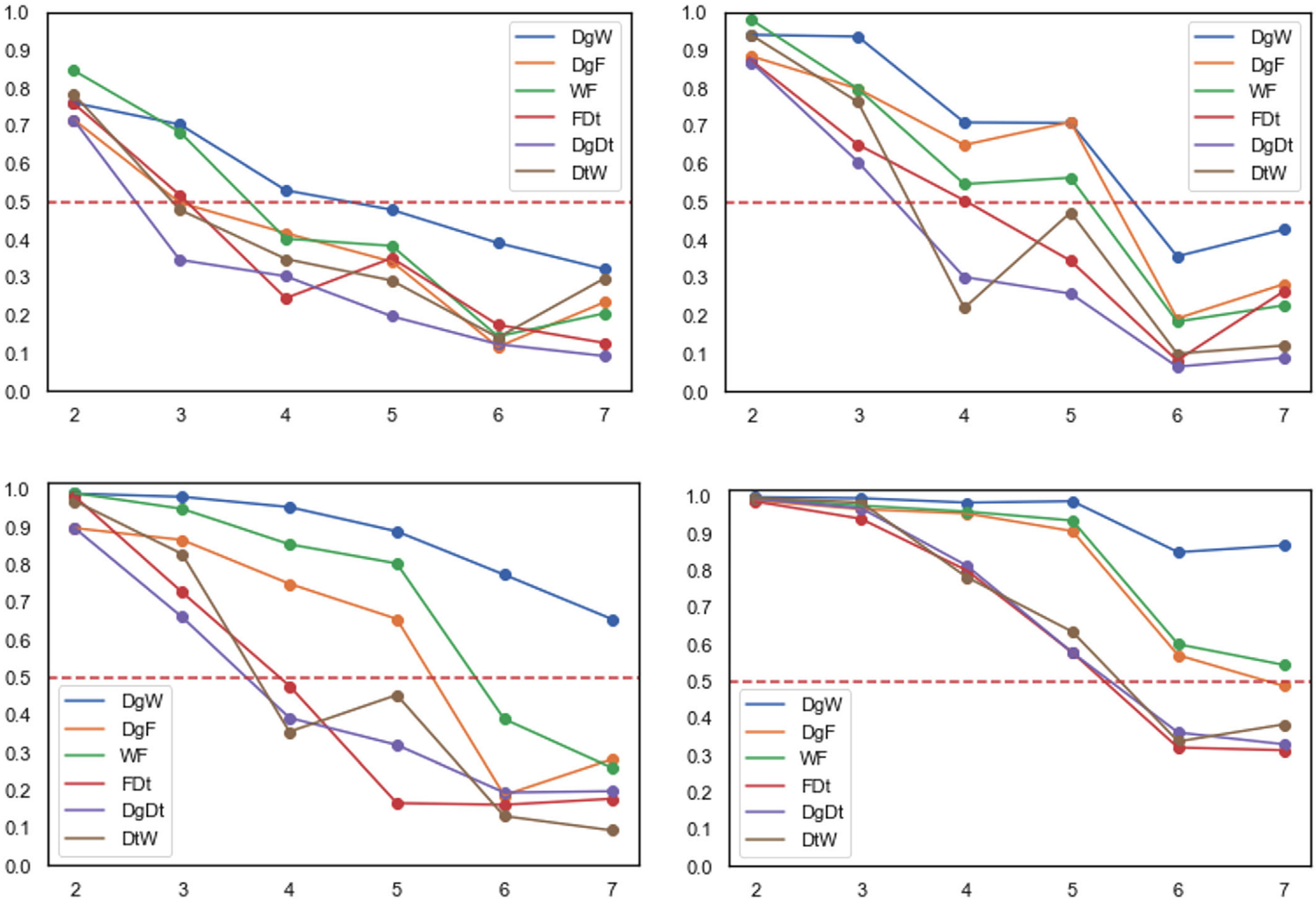

FIGURE 2 Probability of correct mapping (y axis) as a function of number size (x axis) for 2-, 3-, 4-, and cardinality-knowers (left to right and top to bottom). *Note*: DgW (Arabic digits and number words), DgFin (Arabic digits and finger patterns), WFin (number words and finger patterns), FinDot (finger patterns and dot array), DgDot (Arabic digits and dot array), WDot (dot array and number words).

response would be larger for quantities corresponding to numbers #1-to-#3 than to #4. This is because quantities beyond the processing capacity of the PI system would require counting and, as suggested by Sokolowski et al., young children tend to rely on ANS representations. Given its approximate nature, the ANS is more error-prone. Thus, although the task allowed children to count, at least for quantities within their cardinality level (note that there were no time constraints for the response), the pattern of findings described above may be due to young children's reliance on the ANS. Since large quantities require effortful counting, children may have been discouraged and less likely to count. The pattern of responses for cardinality knowers aligns with this possibility. Figure 2 (bottom right panel) shows that even if the probability of a correct response for mappings involving quantities was above 0.5 for numbers up to #5, those probabilities decreased linearly as a function of number size.

An alternative explanation is that the likelihood of a correct response during counting (for mappings involving numbers larger than #3) decreases substantially in young children who are developing their counting skills. In the context of the current study, mappings involving quantities presented randomly arranged dot arrays that potentially impose higher cognitive demands than those in the give-n task. Children must follow the counting sequence and keep track of the dots that have been counted and those that remain. However, this explanation is less plausible because the percentage of trials involving counting was very low (see Figure S2).

Our results diverged from previous studies that have found differences between mappings that involve quantities and symbolic numbers. Children tend to perform worse on mappings between Arabic digits and quantities compared to mappings between number words and quantities (Hurst et al., 2017; Jimenez Lira et al., 2017; Marinova et al., 2021; but see Benoit et al., 2013). Given the similarities in study design, discrepancies could be due to educational factors. Children in our study were attending preschool from the age of three, whereas previous studies recruited children from various contexts such as preschools, day care centers, and museums. Therefore, it is plausible to consider that educational experiences may accelerate the acquisition of mappings between number words, Arabic digits, and quantities. Indeed, there is no reason to support that mappings between number words and quantities precede those between Arabic digits and quantities unless preschool teachers, parents, and caregivers emphasize counting over recognition of Arabic symbols. ECE guidelines regarding the development of the concept of number underscore simultaneous stimulation of different numerical representations. Furthermore, scaffolding the learning of counting does not typically precede the child' stimulation of recognition of Arabic symbols in preschool settings (NCTM, 2000).

In the current study, we also found that children were able to recognize finger patterns above their cardinality knowledge level. Furthermore, children performed worse on mappings between finger patterns and quantities compared to mappings involving finger patterns and symbolic numbers. These findings suggest that children process finger patterns holistically as symbolic codes, rather than perceiving them as non-symbolic quantities. This supports the notion that even children below the age of four recognize finger patterns as symbolic representations of numbers (Gibson et al., 2022). Indeed, our results align nicely with those of Gibson et al. (2022, Experiment 1), showing that cardinality knowers can map finger patterns to number words (#1-to-5) without counting, but our study extends these findings by demonstrating similar mappings between finger patterns and Arabic digits. In addition, Gibson and colleagues suggested that their results are reminiscent of the results of children's mappings between Arabic digits and number words (e.g., Hurst et al., 2017; Jimenez Lira et al., 2017). Our study demonstrates this by showing that the mappings between fingers and symbolic number were similar to pure symbolic mappings.

It is worth noting that the advantage of mappings between fingers and symbolic numbers was not universally observed for all children and quantities. Considering the cardinality level, children with cardinality knowledge exhibited a clear advantage in mappings between fingers and symbolic numbers, but only up to #5. This suggests that mappings differ between finger patterns represented with one hand and patterns represented with two hands. For quantities larger than five, the ability of cardinality knowers to map between fingers and symbolic numbers decreased significantly, indicating that they had not yet acquired holistic representations of finger patterns corresponding to these quantities. Since these children have basic counting skills, they likely relied on counting processes when finger patterns were not processed holistically. Notably, the probability of successfully mapping quantities onto those numbers (#6 and #7) was below 0.5 for these children (cardinality knowers). A possible explanation for these differences between symbol-finger and symbol-quantity mappings that demand counting is the advantage that the spatial arrangement of finger patterns offers in counting. Finger patterns may offload working memory resources associated with keeping track of counted and remaining objects during enumeration. Alternatively, it could be argued that enumeration differences between quantities and finger patterns may involve patterning abilities, as children perceive sets as subsets due to the sub-base-five structure of finger-based representations (Domahs et al., 2008, 2010; Klein et al., 2011). Children may utilize grouping strategies rather than enumerating each finger individually to determine the total number (referred to as "conceptual subitizing" by Clements & Sarama, 2014, or "groupitizing" by Starkey & McCandliss, 2014). Consequently, when presented with a finger pattern corresponding to #6, children can take advantage of the sub-base-five structure of finger patterns (e.g., 5 and 1 fingers) to ascertain its cardinality, either through the combination of both hands or by counting on from the 5-finger pattern. Nonetheless, evidence regarding such combinatorial heuristics in 4-year-olds is scarce. For instance, Starkey and McCandliss (2014) examined the effect of spatial grouping of dot arrays on enumeration in a sample of children in kindergarten through third grade and found no benefit from grouped dot arrays in kindergarten-age children. Therefore, the extent to which preschool children rely on the sub-base-five structure to process finger patterns larger than 5 is an open question that needs further research.

In the case of subset-knowers, our results revealed that children were able to map finger patterns to symbolic numbers above their corresponding cardinality level. Both 3-knowers and 4-knowers exhibited probabilities above 0.5 for mappings between finger patterns and symbolic numbers up to #5. This suggests that children can recognize finger patterns well before fully comprehending the meaning of number words (and Arabic digits) associated with these patterns, aligning with similar findings reported by Gibson et al. (2022, Experiment 3) and Orrantia et al. (2022).

In line with this finding, Gibson et al. (2022) suggested the possibility that finger patterns could act as a useful bridge between symbolic numbers and the quantities they represent, as children in their study mapped more easily between number words and finger patterns than between number words and quantities. This possibility has also been put forward in a recent study in which subset-knowers were trained to assign number words to quantities, either through counting sets and labelling their corresponding sizes with number words or through counting and labelling enriched with finger patterns (Orrantia et al., 2022). The study showed that children who received help through associations between number words, finger patterns, and quantities performed better than those who did not receive assistance with finger patterns. Altogether, these findings suggest a role of finger patterns in establishing connections between symbolic numbers and quantities, probably because of the hybrid nature of canonical finger patterns as "symbols that convey iconic properties". This transparency of finger patterns could make them a steppingstone toward the acquisition of the meaning of number symbols—providing scaffolding (incidentally or purposely) during the developmental stage when children (subset-knowers) are acquiring the meaning of symbolic numbers[2]. It is important to note that finger patterns are not necessarily a decisive tool for the acquisition of symbolic number meaning, but rather they can facilitate this process by providing concrete referents to abstract symbolic numbers.

4.1 | Limitations and future directions

Although results from the mixed model provide evidence of the sequence of acquisition of different mappings, and suggest that finger patterns may serve (potentially) as a bridge between symbolic and non-symbolic quantities, our study is cross-sectional in nature. Therefore, future studies are needed to test this possibility with a longitudinal component. Specifically, if canonical finger representations serve as a bridge between symbolic and non-symbolic (quantities) representations, it is important to know how finger representations contribute to the understanding of the concept of number. For instance, we do not know whether teachers and parents rely on finger representations to scaffold the understanding of the counting principles, or in contrast, canonical finger representations impact the child's ability to label small quantities without counting—subitizing. In a similar vein, future studies could examine the extent to which other familiar forms of structured quantities that also convey iconic properties and are frequently used during the early years—for example, dice-like patterns, are relevant for facilitating associations between symbolic numbers and non-symbolic quantities.

Similarly, although we have tentatively suggested that the educational experiences that children go through might explain some divergences between our results and those found in previous studies, further studies would be needed to investigate the extent to which different educational experiences affect the order in which children acquire mappings between different numerical representations. Some studies suggest that the numerical input children receive influences their development of number knowledge (e.g., Gibson et al., 2019; Mix et al., 2012; O'Rear & McNeil, 2019; Orrantia et al., 2022; Paliwal & Baroody, 2018, 2020). In this sense, children's early numeracy experiences may accelerate the acquisition of some mappings over others. For instance, teacher-led activities incorporating Arabic digits linked to corresponding non-symbolic quantities would promote early knowledge of written symbols.

5 | CONCLUSIONS

The results of the current study showed that young children learn to map between number symbols (i.e., verbal number words and written digits) before they are able to map between these symbols onto the corresponding quantities, and that finger patterns can be considered as another symbolic code to represent numerical information (even for children as young as three years of age). In addition, the current study suggests that finger patterns may play a role in the process by which children learn to map symbols to quantities. These findings would support the implementation of classroom-based and home numeracy activities encouraging the use of finger patterns to best improve young children's early number knowledge.

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CONFLICT OF INTEREST STATEMENT

The authors confirm no conflict of interest. Data are publicly available and will be archived in the USAL Data Repository http://gredos.usal.es/

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Repositorio documental GREDOS at http://hdl.handle.net/10366/153000, reference number 10.14201/gredos.153000.

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ENDNOTES

[1] Although preschool education is not compulsory in Spain, the country boasts nearly full enrolment, with 97% of 4-year-olds enrolled (OECD, 2017). For the purposes of this study, it is important to note that the official Spanish curriculum for this age group establishes the basic competence of "recognizing the most significant basic quantifiers by applying them in the context of play and in interaction with others." Furthermore, the curriculum outlines the development of 'association between different forms of numerical representation' as a key content area.

[2] Beyond their iconic properties, finger patterns can also activate somatosensory and motor representations (Berteletti et al., 2021) that might facilitate children's grasping of the quantity represented by these finger patterns. Thus, compared to other numerical representations, finger patterns have sensory-motor properties that can help to acquire number semantics (we thank an anonymous reviewer for this suggestion).

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