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Do picture books affect counting directionality in preliterate children? Developmental course and potential mechanisms

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ABSTRACT

Why the number line in preliterate children is already consistent with the direction of the script? Here we aimed to 1) show that being read a mirror-printed picture book is able to change lateral biases in counting; 2) trace the development of preliterate biases; and 3) test the role of mental model construction processes. Spanish-speaking 3 and 4 year-olds ($N = 155$, white, 87 female) carried out a task of counting a row of objects and a task in which they built a toy scene before and after being exposed to a mirror-reversed storybook. The left-to-right or right-to-left directionality of their responses was recorded. Only the older group showed pre-test lateral biases. The mirror book changed the lateral biases in counting, and induced a congruent, but smaller change in the model construction task. The two tasks did not correlate, against the implication of shared mechanisms in them.

Introduction

How do people mentally represent numbers? The study of this central question in cognitive science uncovered an unexpected finding: people often represent numbers along a spatial line in their minds, although, in principle, space is not necessary to think about numbers. Dehaene et al. (1993) showed that people are faster to respond to small numbers with left responses and to large numbers with right responses (the SNARC effect), consistently with a mental number line that runs from left to right. The study of the SNARC effect and analogous space-number associations (SNAs) has fueled a large amount of research and theorizing (for reviews, see Cipora et al., 2020; Fischer & Shaki, 2014). Although most of this research has conflated the numerical concepts of magnitude, ordinality, and cardinality, a new consensus has recently emerged that the mental number line is, essentially, an ordinal representation that helps people think about numerical magnitude by means of learnt mappings between the ordinal location of numbers in the numerical sequence and positions in space (Casasanto & Pitt, 2019; Sixtus et al., 2023). Similar ordinal mental lines are used for other abstract concepts, such as time (Bonato et al., 2012).

But why does the mental number line run from left to right? Innate tendencies, possibly due to interhemispheric differences in basic processes, have been observed in newborns and non-human animals (see de Hevia, 2021; Rugani & de Hevia, 2017; for reviews; and Fischer, 2024, for a specific proposal). However, the directionality of the mental number line may change during the life of the individual depending on cultural experiences, such as the exposure to the written script (Dehaene et al., 1993) and cultural artifacts such as number lines, calendars, or charts. Null or reversed SNARC effects have been found in adult readers of right-to-left orthographies, mediated by the degree of consistency of directional practices (Dehaene et al., 1993; Shaki et al., 2009; Zebian, 2005). Also consistent

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with this *reading hypothesis*, the SNARC effect appears after at least one year of formal education in reading (7 year-olds; Gibson & Maurer, 2016; van Galen & Reitsma, 2008; White et al., 2012) or later (Berch et al., 1999), and its size increases with age (Wood et al., 2008). The overall picture suggests that the mapping of numbers onto lateral space arises from innate mechanisms that are later fine-tuned by experience (Göbel et al., 2011), in line with proposals for other abstract concepts (Carey, 2011; Pitt & Casasanto, 2020).

Yet, many details of this view still need to be worked out. One central endeavor has been to trace the developmental trajectory of spatial biases in number representation from a very early age to the adult form. The standard SNARC tasks (reaction times of magnitude or parity judgements on number symbols using left or right keypresses) may be difficult to administer to children and/or fail to capture basic numeric intuitions that children of short age may have. More suitable tasks revealed SNAs in preliterate children. Four-year-olds expect numbers to be ordered from left to right when they search in numbered boxes (Opfer et al., 2010), and map smaller numerosities on the left and larger numerosities on the right (Ebersbach et al., 2014; Patro & Haman, 2012); and 5.5-year-olds show a standard SNARC effect when asked to discriminate the color of a number digit (Hoffmann et al., 2013). Some results suggest that these biases are not just the remnants of early universal left-to-right biases. Shaki et al. (2012) showed that preliterate children between 3 and 6 years old already counted objects in the direction congruent with the script in use in their cultural context, a bias that increased with age. Moreover, some studies fail to find lateral biases in counting tasks in 3-year-olds (Knudsen et al., 2015; McCrink et al., 2017; Patro et al., 2016), and in an ordered search task that previously succeeded to show lateral biases in chicken (unless number and sequence are strongly primed, McCrink et al., 2017; see also West & McCrink, 2021). This suggests that the original, inborn lateral biases wane earlier to be replaced by biases consistent with the directionality of the script (McCrink & de Hevia, 2018).

However, if preschoolers do not yet have extensive practice with reading and writing (nor with number lines, calendars, and the like), where do these script-congruent lateral biases come from? A possibility is that preliterate children acquire these biases from their interactions with adults who show consistent lateral biases (McCrink & de Hevia, 2018; Nuerk et al., 2015). We will refer to this possibility as the *extended reading hypothesis*. One strong candidate is the observation of adult counting, particularly point-and-count routines. Finger counting systematically relates space to numerical magnitude and it probably helps the child discovering the correlation between them (Pitt & Casasanto, 2020). Yet, there is considerable individual and moment-to-moment variation in adult finger counting (Bender & Beller, 2012), and neither the preferred starting hand nor its degree of stability have a clear relation with space-number associations in adults (Hohol et al., 2022). In contrast, when adults point at and count objects, they quite systematically do it following the directionality of the script (see, e.g., Knudsen et al., 2015; Shaki et al., 2012). Thus, adult demonstration of object counting provides consistent experiences linking magnitude with the lateral axis in a particular direction.

Other consistent directional practices may also exert an influence (see Nuerk et al., 2015, for a review). In the present study we focus on the interactions that occur when caregivers read and tell stories from illustrated books to their children. These interactions begin as early as 3 months of age and often occupy many hours in literate families during the early years of the child (Rossmannith et al., 2014). McCrink et al. (2018) observed that parents tend to point and gesture accordingly to script direction when creating stories for their children from pictures and slideshows. Moreover, the spatial organization of the pictures in children's books also tends to follow the directionality of the script (Göbel et al., 2018), likely reinforcing adult gestural tendencies. Additionally, the turning of the pages generates a spatial flow in the story, and parents also often point to the written words as they read them. All of these factors increase the preliterate child's exposure to consistent laterally asymmetric stimuli and actions.

All the evidence reviewed above in support of the extended reading hypothesis is almost entirely correlational. Comparisons between participants from different cultures and languages as well as comparisons of different age groups do not allow for causal inferences, as participants cannot be randomly assigned to the conditions in these designs. The studies that come closest to providing causal evidence are those by Shaki and Fischer (2008) and Fischer et al. (2009), who observed variations in the SNARC effect in Russian-Hebrew bilinguals after reading left-to-right (Russian) or right-to-left (Hebrew) texts. However, they suffer from the problem that the crucial control condition of auditory-only presentation induced similar changes in the SNARC effect in one of the studies (Fischer et al., 2009; see Pitt & Casasanto, 2020, for detailed discussion).

In the field of cognitive development only one study has provided causal evidence that being read an illustrated book by a caregiver can modify SNAs in preliterate children. Göbel et al. (2018) read a storybook either in its original (left-to-right) or mirror image (right-to-left) form to 3- to 5-year-old preliterate children raised in a British (left-to-right) or Arab (right-to-left) linguistic environment, and assessed the direction in which they counted a set of objects both before and after the reading experience. The book increased the number of children who counted with the same directionality as the book, in both cultures. As the selected storybook contained instances of counting, a follow-up study (Study 3) removed all counting from the book, and the two versions of the book were read to a group of British children, with analogous (though weaker) results. Because the directionality of the reading material was experimentally manipulated, this study establishes a causal relation between book exposure and counting direction in preliterate children, supporting the extended reading hypothesis.

Given the scarcity of causal evidence regarding this question, the first goal of the present study was to replicate the key condition of Göbel et al.'s (2018) Study 3 (hereafter GMFS3), which provides the clearest test of the effect of picture books by removing all instances of counting from the story. We focused on the critical condition and presented the same storybook in its mirror form (right-to-left) to a group of Spanish-speaking preschoolers (left-to-right context), and assessed their initial counting biases and how these changed after the book experience. We also aimed to trace the developmental course of initial counting biases during the first two years of preschool,¹ by comparing children between the ages of 3 and 5.

¹ In Spain, the preschool stage lasts three years. See the Participants section for more details.

Dropping the standard (left-to-right) book condition was motivated by practical considerations: to maximize the sample included in the critical mirror book condition. Technically, this choice renders the design unable to distinguish between the effects of exposure to a mirror book from exposure to any book, or even from just the passing of time. However, all relevant published studies have described increases of lateral biases with age in the direction that agrees with the local script as children progress through their formal education (see [Shaki et al., 2012](#), among many others). Moreover, [Göbel et al. \(2018\)](#), using the exact same picture book as used here, showed that its presentation in standard form did not affect left-to-right counting biases, while in mirror form it reduced them. Therefore, the finding of a reduction in the left-to-right bias or even the induction of a right-to-left bias after exposure to the mirror book is unlikely the result of factors other than the right-to-left directionality of the mirror book.

As an additional goal, we also wanted to explore the underlying mechanisms through which being read storybooks can change SNAs. [Göbel et al. \(2018\)](#) tested the possibility that the cause was the attentional, ocular, and pointing movements that occur while scanning the storybook, but found no supporting evidence. Thus, they suggested that the mechanism is linked to the comprehension of the sentences and the overall storyline, and pointed toward the activation of the mental time line, which in turn would affect the number line. We here explore a different potential mechanism that also requires language processing. Santiago and collaborators ([Román et al., 2013, 2018](#)) proposed that SNAs and other script-linked lateral biases such as those observed in time ([Ouellet et al., 2010](#)) and agency ([Maass & Russo, 2003](#)) are the result of processes of mental model construction in working memory, as detailed in the Coherent Working Models theory ([Santiago et al., 2011](#)). Under this view, working memory is an internal space analogous to external space. The mental model of the situation is a spatial model populated by elements that capture the relevant aspects of the situation in a way that facilitates meeting task demands (see [Santiago et al., 2011](#), for a detailed description of the relevant representations and processes). When the goal is to understand a written sentence, the mental model contains both the input sentence itself as well as an analogical representation of its meaning: the described situation, event, or series of events. This theory posits a pressure towards maximizing the internal coherence of mental models, due to the limited capacity of working memory. This pressure generates a tendency to place the contents of the sentence in the model in the same spatial order as they appear in the written text. In most languages, sentences mention first the agent, then the object, so agents tend to be placed to the left of objects in the mental model. As people tend to mention events in the order in which they occurred ([Grice, 1975](#)), the temporal flow of events, encoded both within and across sentences, also tends to be represented in the model in the same direction of the script. Extended practice of these strategies of mental model construction turns them into habits that generalize to auditory language. Auditory descriptions of static situations provide a direct testing ground for lateral biases in mental model construction. [Román et al. \(2013\)](#) asked participants to draw scenes described by sentences like “the table is between the lamp and the TV”. Readers of left-to-right scripts tended to place the lamp on the left and the TV on the right of the table, whereas right-to-left readers showed the opposite preference. [Román et al. \(2015\)](#) showed that a brief experience reading text with different directionalities is enough to change these spatial biases accordingly, supporting a causal link. When stories are presented visually, such as in wordless comics, the directionality of the sequence of frames exerts the same effect than the visual sequence of event mentions in written sentences. Indeed, understanding a speechless comic whose frames are presented from right to left was able to reverse these spatial biases in an adult sample ([Román et al., 2018](#)). We propose that such biases generalize naturally to situations in which the elements of a static situation are to be scanned for naming or counting (see also [Román et al., 2013, 2018; Santiago et al., 2011](#)). To provide support for this view, in the present study we examined whether the experience with the mirror-reversed picture book is also able to change the spatial biases of mental model construction in preliterate children.

Summing up, the present study examined initial lateral biases in both a counting task and a mental model construction task in preliterate 3- to 5-year-old children being raised in a left-to-right culture (Spain). We then exposed them to a mirror-reversed (right-to-left) picture book, and reassessed their lateral biases in both tasks again. There were three research questions:

1) Is the experience of being read a mirror-printed picture book able to change lateral biases in counting? We expected that the mirror book experience would increase the tendency to count right-to-left in the whole sample (H1.1), and both in younger (H1.2) and older preschoolers (H1.3).

2) What is the developmental course of preliterate lateral biases in counting? In other words, are there initial counting biases in younger and older preschoolers? Do those biases get stronger with age? We expected that the whole sample of preliterate preschoolers would show a significant lateral counting bias at pre-test (H2.1). We also expected that such an initial left-to-right bias in the younger group would be null (H2.2) or weaker (H2.3), but it would become clearer in older preschoolers (H2.4).

3) Are lateral biases in mental model construction processes linked to lateral counting biases? We expected that the mental model construction task would show the same initial lateral biases than the counting task in the whole sample (H3.1), and both younger (H3.2) and older (H3.3) preschoolers. We also expected that the mental model task would be affected by exposure to the mirror book in the whole sample (H3.4), and both younger (H3.5) and older (H3.6) preschoolers. Finally, we also expected a significant between-task correlation at both the initial (H3.7) and final tests (H3.8).

The counting task and the mirror-reversed book experience were close replications of GMFS3 with only minor adaptations. The model construction task was a children-adapted version of the drawing task developed by [Román et al. \(2013\)](#). Minimum sample size was established to ensure over 90% power to detect an effect of the same size as observed by GMFS3, and actual sample size nearly doubled that amount in each age group.

Methods

Transparency and openness

We report how we determined our sample size, as well as all data exclusions, all manipulations, and all measures in the study. All

materials, anonymized raw data, and analysis scripts are publicly available at <https://osf.io/ufn9k>. The study was not preregistered; therefore, all results should be considered exploratory in the sense proposed by Wagenmakers et al. (2012).

Design and analysis

We used a pre-post design with two dependent measures: counting directionality and model construction directionality. Pre-existing spatial biases were analyzed using chi-squared tests, and pre-post differences by McNemar tests. Sequential effects between tasks were examined using binary logistic regressions, also including additional predictors. All analyses were performed using R (R Core Team, 2018), version 3.6.3.

Sample size and power

We estimated the sample size required to achieve 90% power to observe effects of the same size as previously reported at $\alpha = 0.05$ in the current design and analytical strategy (see supplementary materials for a detailed description and R script). For the counting task, the initial bias reported by GMFS3 was of size $\phi = .721$. To detect this effect at the established power and alpha, a sample size of 20.21 (20 participants) is needed. The pre-post change observed in the counting task in the mirror book condition was of size Cohen's $g = 0.43$, which requires a sample size of 37 participants. The initial bias in the model construction task is more difficult to estimate, as prior studies have used adults instead of children, and a drawing task instead of the manipulative task we used here (described below). Keeping these caveats in mind, Román et al. (2015) reported an effect size of $\phi = .6$ in their control group (no directional induction), which requires a sample of 29.18 (29 participants). Even more difficult is to estimate the effect size of the change in this task, as no prior related study has used a pre-post design. Thus, we used the estimation from the counting task. All in all, we set sample size to a minimum of 40 participants per age group, roughly the same number that was used by GMFS3 in each book condition (standard vs. mirror). Due to availability, the final sample nearly doubled this number, what means that the present design had greater power to detect smaller effects than GMFS3 within each age cohort.

Participants

The sample consisted of 158 children from public schools of the metropolitan area of Granada (Spain). Age groups were defined using the academic course. In Spain, the preschool stage comprises three academic courses, the 3 y., 4 y., and 5 y. courses. Children are assigned to courses depending on their chronological age at December 31st. That is, the 3 y. class includes children that turn 3 years old before December 31st of the ongoing academic year. As testing for the present study occurred always after that date, the age of children in each group ranged from their nominal course age until one more year. Table 1 provides a detailed description of the groups. Additional demographic data are not available on an individual basis, but the area of Granada is majoritarily ethnically white of Spanish descent, with a 11.7% immigrant population from other countries (source: National Institute of Statistics, 2022 census).

Although there is a slight overlap in terms of chronological age between the two groups, the lateral biases that we are studying here are hypothesized to depend on exposure to directional practices. Thus, besides being, on average, one year older, the older group had one more academic year of exposure to such practices than the younger group.

The study was approved by the Ethical Committee of the University of Granada (469/CEIH/2018). Informed consent was obtained from the children's legal guardians.

Table 1
Participant characteristics.

| | Groups | |
|--------------------------------------|------------|------------|
| | 3 y. class | 4 y. class |
| N | 83 | 75 |
| Females | 45 | 42 |
| Left-handers | 3 | 5 |
| Mean age | 3.77 | 4.77 |
| Age range | 3.0—4.4 | 4.0—5.3 |
| SD age | 0.31 | 0.33 |
| Identified no vowel | 54 | 5 |
| Identified all five vowels | 10 | 38 |
| Identified no consonant | 52 | 21 |
| Identified more than four consonants | 5 | 8 |
| Read no words | 82 | 64 |
| Read one or two words | 1 | 9 |
| Read more than two words | 0 | 2 |
| Read all words | 0 | 1 |
| Arabic family | 1 | 1 |
| Did not pay attention to the book | 2 | 1 |
| Knew the book | 6 | 15 |

Materials

Two different versions of the counting and the mental model construction tasks were presented at pre-test and post-test. The counting task used four toy plastic coins at pre-test, and four small white candles at post-test. The model construction task used small toy models resembling household items: a lamp, bed, and chair at pre-test, and a stove, kitchen sink with cabinet, and rocking chair at post-test (see Fig. 1). The book experience used a mirror version of the book ‘The Very Hungry Caterpillar’ (297x210mm). The book was modified as described in GMFS3 by substituting pages with five objects for all counting pages. All text was replaced by meaningless pseudo-font symbols but keeping their positions on the page. The book was bound on the right and the pages were turned left to right. Finally, we used two sheets, one with lowercase letters of the alphabet (a, e, i, o, u, m, b, c, s, d, p, r), and the other with lowercase common words (mummy, daddy, car, house, duck, goose, gift, flower), to check that the child was unable to read.

Procedure

The study was run at the school. The experimenter took the child to a quiet room and sat with him/her in front of a table. We counterbalanced whether the experimenter sat on the left or right of the child. The session consisted of six steps: the two pre-test tasks (counting and model construction), the book experience, the two post-test tasks, and the literacy check. The order of the counting and model construction tasks was also counterbalanced.

Both the counting and model construction tasks were adapted for their use with preschool children. To make the tasks more motivating for the children, we used two toy characters. In the counting task, the experimenter would show one character and say: “This is Felisa. Felisa doesn’t know how to count. Can you help Felisa counting some objects?” Felisa would then be removed and the child was asked to close her eyes. Then, the four objects were placed in a row in front of them, centered. The child was then asked to open their eyes, point and count the objects. Counting hand and starting side was recorded on the spot. The only differences with the counting task used by GMFS3 was the toy character and the counted objects.

We developed a manipulative version of Román et al.’s (2013) model drawing task. As we expected problems with the understanding of the term “between” in this age range (Simms & Gentner, 2019), we placed the central object and asked the children to place the two lateral objects one after another using the term “beside.” Specifically, the experimenter would show another character and say: “This is Alonso. Alonso is preparing his new house. Can you help him arrange some furniture in his bedroom?” (“kitchen” at post-test). Alonso was then removed from sight and a toy bed was placed in front of the child, facing her, centered. “Look, we have here a lamp and a chair.” Both objects were shown to the child. Then, one was handed to them. “Please, put the chair beside the bed”. After the child did, the experimenter handed the other object and continued: “Now put the lamp on the other side”. The resulting model was then photographed, and response hand and starting side recorded.

After the pre-test, the experimenter “read” the mirror book from memory, while pointing to the pseudowords, making comments, and asking the child to find the mentioned objects and point at them on the book’s pages. On pages with multiple objects, the experimenter said “the caterpillar ate plums...”, while pointing to each plum from right to left (and did the same for the other objects). The book experience was followed by the two post-test tasks and the final literacy check.

Finally, the experimenter recorded whether the child knew the book before, and whether they had paid no attention to the book during the session. From their teachers we collected information on whether Arabic might be used in the child’s family, and whether the child was left-handed.

Results

Three children did not pay attention to the mirror book during the session and were filtered out. This left 81 children in the 3 y. group and 74 in the 4 y. group. At the OSF repository we also provide supplementary commands to run analyses excluding the children that were distracted (3), plus the child who was able to read, the left-handers (8), those who knew the book (21), and/or whose family

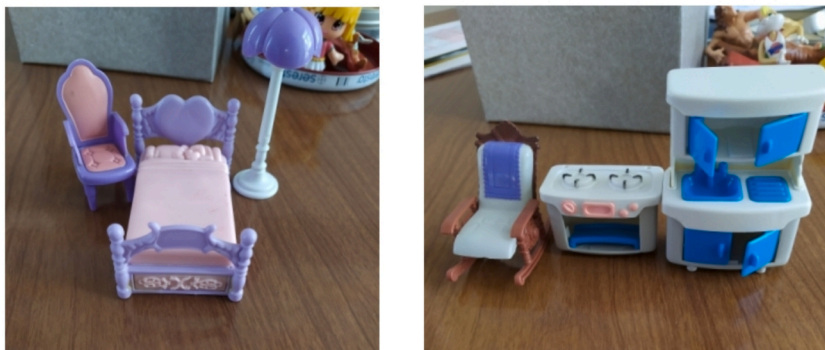


Fig. 1. Models produced by one of the participants in the pre-test and post-test model construction tasks.

used Arabic at home (2), as these factors might also affect the results (final $N = 124$). However, the pattern of results remained unchanged.

The top panel in Fig. 2 and Tables 2 and 3 show the results pooling together both age groups. At pre-test, the children exhibited an

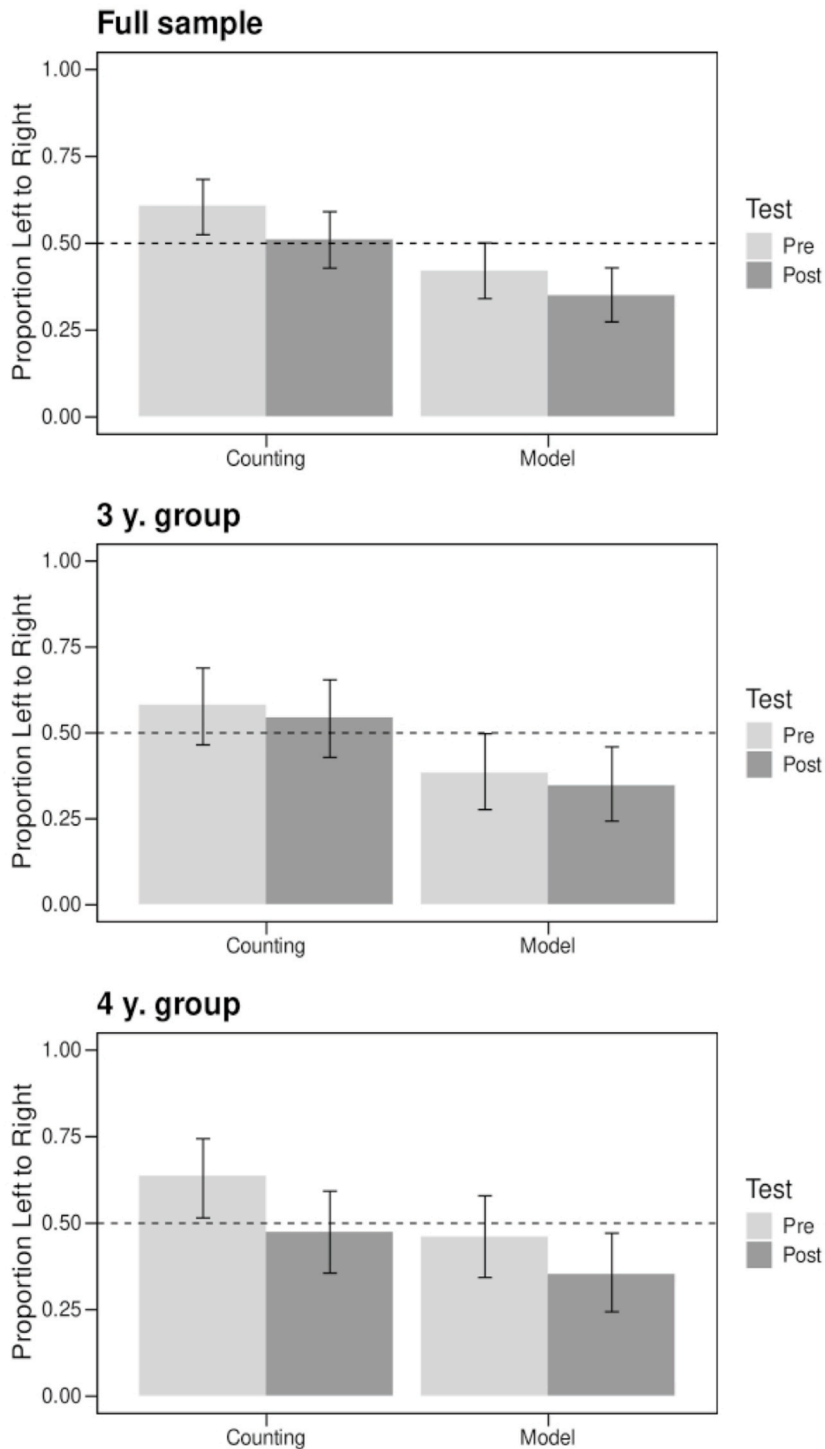


Fig. 2. Proportion of children in the full sample that showed left-to-right behavior in the counting and model construction tasks before and after the mirror book experience. Top panel shows pooled results and center and bottom panel show results within each age group. Note: Error bars show Clopper-Pearson 95% CIs.

initial left-to-right bias in counting (60.6% left-to-right vs. 39.4% right-to-left; $\chi^2(1, N = 155) = 7.03; p = .008; \varphi = 0.21$), but a right-to-left bias in model construction (41.9% left-to-right vs. 58.1% right-to-left; $\chi^2(1, N = 155) = 4.03; p = .04; \varphi = 0.16$). The mirror book experience produced a significant change in counting direction (McNemar's $\chi^2(1, N = 155) = 5.03; p = .02$; Cohen's $g = 0.19$) and a smaller, non-significant change in model construction (McNemar's $\chi^2(1, N = 155) = 1.75; p = .19$; Cohen's $g = 0.10$). These changes produced that, at post-test, there was no lateral bias in counting direction (51% left-to-right vs. 49% right-to-left; $\chi^2(1, N = 155) = 0.06; p = .81; \varphi = 0.02$), and a clearer right-to-left bias in model construction (34.8% left-to-right vs. 65.2% right-to-left; $\chi^2(1, N = 155) = 14.25; p < .001; \varphi = 0.30$). Preference in counting direction and model construction direction were not associated neither at pre-test ($\chi^2(1, N = 155) < 0.001; p = .98; \varphi = 0.02$) nor at post-test ($\chi^2(1, N = 155) < 0.001; p = .99; \varphi = 0.01$).

Fig. 2 (middle panel) shows the 3 y. class (see also Tables 2 and 3). In this group there was no lateral bias at pre-test in the counting task (58% left-to-right vs. 42% right-to-left; $\chi^2(1, N = 81) = 2.09; p = .15; \varphi = 0.16$), but there was a right-to-left bias in model construction (38.3% left-to-right vs. 61.7% right-to-left; $\chi^2(1, N = 81) = 4.46; p = .03; \varphi = 0.23$), and the mirror book experience did not change lateral preferences significantly (counting: 12 children changed from left-to-right to right-to-left versus 9 children changed from right-to-left to left-to-right, McNemar's $\chi^2(1, N = 81) = 0.19; p = .66$; Cohen's $g = 0.07$; model construction: 17 versus 14 children, McNemar's $\chi^2(1, N = 81) = 0.13; p = .72$; Cohen's $g = 0.05$). After the mirror book experience, counting remained without lateral biases (54.3% left-to-right vs. 45.7% right-to-left; $\chi^2(1, N = 81) = 0.60; p = .44; \varphi = 0.09$), and the right-to-left bias in model construction was clearer (34.6% left-to-right vs. 65.4% right-to-left; $\chi^2(1, N = 81) = 7.72; p = .005; \varphi = 0.31$). Counting and model construction direction were not associated (pre-test: $\chi^2(1, N = 81) = 0.06; p = .81; \varphi = 0.05$; post-test: $\chi^2(1, N = 81) = 0; p = 1; \varphi = 0.01$).

Fig. 2 (bottom panel) shows results in the 4 y. class (see also Tables 2 and 3). At pre-test, children showed a significant left-to-right bias in counting (63.5% left-to-right vs. 36.5% right-to-left; $\chi^2(1, N = 74) = 4.07; p = .04; \varphi = 0.24$) and no bias in model construction (45.9% left-to-right vs. 54.1% right-to-left; $\chi^2(1, N = 74) = 0.49; p = .49; \varphi = 0.08$). The mirror book induced a significant change in counting bias (15 children changed from left-to-right to right-to-left counting versus only 3 children showing the opposite change, McNemar's $\chi^2(1, N = 74) = 6.72; p = .01$; Cohen's $g = 0.33$), and a smaller, non-significant change in model construction (17 versus 9 children, McNemar's $\chi^2(1, N = 74) = 1.88; p = .17$; Cohen's $g = 0.15$). As a result, counting at post-test ended having no lateral bias (47.3% left-to-right vs. 52.7% right-to-left; $\chi^2(1, N = 74) = 0.22; p = .64; \varphi = 0.05$), and the small change in model construction was enough to produce a significant final right-to-left bias (35.1% left-to-right vs. 64.9% right-to-left; $\chi^2(1, N = 74) = 6.54; p = .01; \varphi = 0.30$). In this age group, counting and model construction direction were also not associated (pre-test: $\chi^2(1, N = 74) = 0.002; p = .96; \varphi = 0.03$; post-test: $\chi^2(1, N = 74) < 0.001; p = 1; \varphi = 0.02$).

To assess whether children in the 3 y. class were more inconsistent than those in the 4 y. class, we compared how many changed versus those who did not change the directionality of their responses in each group within each task. In the counting task, 25.9% of children in the 3 y. class changed their response directionality versus 24.3% in the 4 y. class, a difference that was not significant ($\chi^2(1, N = 155) = 0.002; p = .96; \varphi = 0.02$). In the model construction task, the difference was also not significant (38.3% change in the 3 y. class versus 35.1% in the 4 y. class; $\chi^2(1, N = 155) = 0.057; p = .81; \varphi = 0.03$). Thus, the two age groups did not differ in overall consistency of response.

We also explored sequential effects between the tasks at pre- and post-test using logistic regressions. There were no sequential effects neither at pre-test (counting over model construction: $\beta = 0.16, p = .72, OR = 1.18$; model construction over counting: $\beta = 0.06, p = .90, OR = 1.06$) nor at post-test (counting over model construction: $\beta = 0.64, p = .18, OR = 1.90$; model construction over counting: $\beta = -0.80, p = .10, OR = 0.45$).

Other analyses explored the potential effects of handedness, child location with respect to the experimenter, prior knowledge of the book, and hand used to perform the task, both at pre-test and post-test. At pre-test, we also included the alternative task as a predictor, and at post-test we added both pre-tests tasks as predictors. At pre-test, counting directionality was only related to response hand ($\beta = 4.28, p < .001, OR = 72.17$; 69% of the children counted with the hand ipsilateral to the starting object). Other factors had no effect (see full output in Table S3). Pre-test model construction was also related to the hand used for toy placement ($\beta = 1.67, p < .001, OR = 5.32$; 71.6% ipsilateral starters), child location ($\beta = -1.00, p = .009, OR = 0.37$; 65.2% experimenter-side starters), and also handedness ($\beta = 2.39, p = .048, OR = 10.87$; 61.9% started on their dominant side; Table S4). At post-test, counting directionality was also related to the responding hand ($\beta = 2.89, p < .001, OR = 17.97$) and, additionally, to pre-test counting directionality ($\beta = 2.30, p < .001, OR = 9.94$; Table S5). Similarly, post-test model construction was related only to the response hand ($\beta = 1.20, p = .007, OR = 3.31$) and to pre-test model construction ($\beta = 0.77, p = .04, OR = 2.17$; Table S6).

Table 2
Counts of left-to-right behavior in the counting task in the two age groups and the full sample.

| | Post-test | | | Total |
|-------------|---------------|---------------|---------------|-------|
| | Pre-test | Left-to-right | Right-to-left | |
| 3 y. class | Left-to-right | 35 | 12 | 47 |
| | Right-to-left | 9 | 25 | 34 |
| 4 y. class | Left-to-right | 32 | 15 | 47 |
| | Right-to-left | 3 | 24 | 27 |
| Full sample | Left-to-right | 67 | 27 | 94 |
| | Right-to-left | 12 | 49 | 61 |
| | Total | 79 | 76 | 155 |

Table 3

Counts of left-to-right behavior in the model construction task the two age groups and the full sample.

| | Pre-test | Post-test | | Total |
|-------------|---------------|---------------|---------------|-------|
| | | Left-to-right | Right-to-left | |
| 3 y. group | Left-to-right | 14 | 17 | 31 |
| | Right-to-left | 14 | 36 | 50 |
| 4 y. group | Left-to-right | 17 | 17 | 34 |
| | Right-to-left | 9 | 31 | 40 |
| Full sample | Left-to-right | 31 | 34 | 65 |
| | Right-to-left | 23 | 67 | 90 |
| | Total | 54 | 101 | 155 |

Discussion

The present study had three main goals: 1) to replicate GMFS3 finding that a short experience with a right-to-left picture book devoid of any counting is able to reduce or even reverse left-to-right biases in counting; 2) to replicate the GMFS3 finding that children raised in a left-to-right culture have left-to-right counting biases before learning to read, and to trace the developmental course of counting biases by comparing a 3 y. and a 4 y. group; and 3) to test whether a similar pattern of biases and bias changes can be observed in a model construction task. Improving on the original study, we used a sample that nearly doubles GMFS3 and carefully checked that participants were at a very early stage of development of reading skills.

The counting task did replicate the findings of the critical mirror book condition of GMFS3 in the analysis of the full sample of preliterate readers. There was a significant left-to-right bias at pre-test (hypothesis H2.1), and the bias was significantly reduced by exposure to a right-to-left picture book (H1.1). Therefore, exposure to picture books is able to induce lateral biases in counting and, thus, joins other directional experiences (such as the observation of adult counting, see [Nuerk et al., 2015](#)) as potential causes of the lateral SNAs shown by preliterate children, as proposed by the extended reading hypothesis (see the Introduction). As a caveat, it should be kept in mind that the present design only used the mirror book condition and, technically, it can not distinguish the effect of the directionality of the book from the effect of the exposure to any book or to even the mere passing of time. However, the finding of a reduction in the left-to-right bias, while the same book in standard form has been shown to have no effect (as in GMFS3) or even increase the left-to-right bias (as in [Göbel et al., 2018, Study 2](#)), makes unlikely these alternative interpretations.

However, the effects were smaller than expected. First, GMFS3 reported that 86.2% of children counted from left to right at pre-test, whereas only 60.8% did in our sample ($\varphi = 0.72$ vs. $\varphi = 0.22$, respectively: a large vs. a small effect by [Cohen's, 1988](#), standards). When left-handers, book knowers, and the only child able to read were also filtered out, this proportion was even smaller (58.9%; see Supplementary materials). Age cannot explain the difference in effect size between the two studies, as the mean age in GMFS3 was 3.9 y. versus 4.25 y. in the present sample. Preschool education starts at the same age in the UK and Spain. As GMFS3 did not measure actual reading skills, there is a possibility that their participants were somewhat more familiar with reading than children in the present sample. However, this possibility conflicts with the large change in lateral biases observed by GMFS3 (Cohen's $g = 0.43$; see section 2.3) whereas we found a medium-sized change (Cohen's $g = 0.19$). If GMFS3 children were more advanced in reading acquisition, we would expect them to be less susceptible to change, not more. At the moment, the reasons for these differences are unclear, but it is important to keep in mind that they may be just random variation between studies. In such case, the present, larger sample renders a more precise estimate of effect size.

The present study not only provides a needed replication of GMFS3 findings, but also explores the developmental course of preliterate lateral biases. In the 3 y. group, the initial left-to-right tendency was small and did not reach significance (H2.2), whereas it was larger and significant in the 4 y. group (H2.4), in agreement with studies that fail to find lateral biases in counting tasks in younger preschoolers ([Knudsen et al., 2015](#); [McCrink et al., 2017](#); [Patro et al., 2016](#)). This supports the developmental course suggested by [McCrink and De Hevia \(2018\)](#), where inborn, early left-to-right biases wane to be replaced later with biases linked to the direction of the script. The force driving lateral SNAs during this second stage of development must be the accumulation of directional experiences and not maturation processes linked to age, because SNAs develop consistently with the direction of the script. It should be noted, though, that this account based on directional practice is not fully consistent with 1) comparable within-participant consistency between groups; and 2) smaller susceptibility of the 3 y. group to the right-to-left book experience than the 4 y. group, as the change induced by the mirror book was larger and only significant in the latter (supporting hypothesis H1.3, but not H1.2). If script-linked lateral biases are less consolidated in the younger group, this group should be less consistent and more reactive to directional experiences than older preschoolers.

The model construction task was introduced as a way to measure lateral biases when constructing mental models from linguistic descriptions. Following the Coherent Working Models theory ([Santiago et al., 2011](#)), mental model construction processes in working memory are one mechanism by which several kinds of script-linked lateral biases (such as in time, agency, static scenes, and counting, among others; see the Introduction) develop. Thus, we expected similar and correlated lateral biases in counting and model construction. [Román et al.'s \(2013\)](#) drawing task was adapted here for use with preschool children by turning it into a 3D manipulative task where plastic toys were placed on either side of a central toy.

Against expectations (hypotheses H3.1, H3.2, and H3.3), this task showed a right-to-left bias at pre-test, both in the full sample and the younger group, but it provided some support to our predictions (H3.4, H3.5, and H3.6) by showing that the mirror (right-to-left) book did produce an increase in the right-to-left bias. The change was not large enough to reach significance but it was able to make the

bias statistically clearer at post-test in the two age groups and the full sample. The results also failed to correlate with the counting task, neither at pre-test (H3.7) nor at post-test (H3.8). There were even no cross-task sequential effects at any testing point, and each task at post-test was only affected by the same pre-test task (but not the other). Therefore, we conclude that the book experience had a weak effect on directional habits in mental model construction in the same direction as it affected counting, but we lack additional evidence that the lateral biases in both tasks share underlying mechanisms, contrary to predictions from the Coherent Working Models theory. Considered together with the final experiment in Göbel et al. (2018)'s study, which ruled out ocular and attentional movements while observing an adult pointing to a moving object, and with Patro et al. (2016), where it was the child who moved the object, the mechanisms by which the mirror book experience changes lateral biases in counting remain unclear.

The mental model construction task holds promise for future studies, as it detected some influence of the picture book experience. Its mechanisms, whether shared with the counting task or not, are worth studying on their own and may also participate in other lateral biases (e.g., the agency bias; Maass & Russo, 2003). However, there are hints that some aspects of the model construction task can be improved, possibly allowing for a more reliable detection of the relevant lateral biases. First, this task seems to be more affected by motoric factors than the counting task. The directionality of both tasks was strongly related to the responding hand, as documented by Patro et al. (2015), but only model construction, not counting, was also significantly affected by handedness at both pre- and post-test. This suggests that, in counting, children choose the hand ipsilateral to the side they want to start counting from, but in model construction, they choose first the hand they want to use (usually the dominant hand) and then construct the model starting from the ipsilateral side. Second, one aspect of the model task used in the present study may have reduced the influence of script-linked biases. We modeled the task on the drawing task used by Román et al. (2013), in which the participant is asked to draw a scene such as “the table is between the lamp and the TV”. There, the participant needs to hold all three objects simultaneously in memory, construct a mental model of the scene, and plan an ordered sequence of drawings. Adult data showed that the task is a valid index of processes of mental model construction (Román et al., 2013, 2015, 2018). As asking preschoolers to draw such a sentence seemed beyond their capabilities (specially the understanding of the term “between”), in the present adaptation of the task, after placing one toy on the table, the experimenter showed the child the two toys, but then gave the child only one of them, asking him/her to place it “besides” the object on the table. In principle, the task implies order: as the child knows that two toys are to be placed, s/he has to decide on which side to start, and the final array is a linear array. In hindsight, however, on some trials children may have carried out the task in a way that does not imply order decisions. The child may have simply grabbed the first toy with the dominant hand and place it wherever it was motorically more comfortable. It is important to emphasize, though, that the task showed some indications of being affected by the mirror book experience: the right-to-left bias observed at pre-test in the 3 y. class became larger in magnitude and even more significant at post-test, and the non-significant bias at pre-test in the 4 y. class became a significant right-to-left bias at post-test. The task is, therefore, able to capture the intended linear ordering processes, but needs to be fine-tuned to provide a cleaner measure of them. Given that this has been the first implementation of this task and its partial success, we have learned important lessons for future implementations.

To conclude, the present study showed that preliterate Spanish-speaking children in the 3 y. preschool class do not exhibit significant left-to-right biases in counting and those biases are not influenced by the experience of being read a right-to-left picture book. At the 4 y. class, children do show clear lateral counting biases which were responsive to the book experience. This supports the extended reading hypothesis: directional experiences are able to induce lateral SNAs before children learn to read, and one of those directional experiences is “reading” picture books with caregivers. The present study provided a more precise estimation of effect size, which was smaller than previously reported, with important implications for the design of future studies. The mirror book experience was also able to produce small changes in lateral biases in model construction, a previously undocumented effect in preliterate children. Counting and model construction biases went in the same direction, but were uncorrelated, leaving the possibility of shared underlying mechanisms pending of further exploration.

Public significance statement.

Children show lateral directional biases in number processing (e.g., preferences toward left-to-right or right-to-left counting) that are linked to the directionality of the written script. However, they start showing these biases before they actually learn to read. Where do preliterate lateral biases come from? We here trace their developmental course, corroborate that early exposure to children's storybooks plays a causal role, and explore whether they are related to processes of mental model construction.

CRediT authorship contribution statement

Julio Santiago: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ana Jiménez:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Laura Rivera:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Francisca Serrano:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration of generative AI and AI-assisted technologies in the manuscript preparation process:

During the preparation of this work the authors used ChatGPT in order to revise the English language in some sentences. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Data availability

The data and analytic code necessary to reproduce the analyses presented here are publicly accessible at <https://osf.io/ufn9k>

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