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How Literacy-Related Experience Shapes Spatial-Numerical Associations: A Developmental Shift in Vertical Number-Space Mapping

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Abstract

Spatial-numerical associations (SNAs) reflect systematic mappings between numerical magnitude and spatial directionality and are shaped by both biological predispositions and cultural experiences. The present study examined the developmental emergence of horizontal and vertical SNAs in Japanese-speaking children exposed to both left-to-right and top-to-bottom writing conventions. In Study 1, children aged 2–7 years and adults completed card-ordering, counting, and sticker-placing tasks in which stimuli were arranged horizontally or vertically. Horizontal SNAs showed a left-to-right bias in children aged 5 and older. In contrast, vertical SNAs changed with age, shifting from a bottom-to-top bias in early childhood to a top-to-bottom bias by around age 7. In Study 2, we examined whether this developmental shift was related to literacy-related experience. Logistic regression analyses showed that hiragana character-sound knowledge significantly predicted top-to-bottom vertical SNAs in 5- to 7-year-olds, controlling for age and nonverbal intelligence. These results demonstrate that SNAs are not fixed mappings but rather flexible representations partially shaped by literacy-related experiences.

Keywords: spatial-numerical associations (SNAs); numerical cognition; character-sound knowledge

Background

Spatial-numerical associations (SNAs) reflect systematic mappings between numerical magnitude and spatial directionality. A prominent example is the tendency to associate smaller numbers with the left side of space and larger numbers with the right, often described as a mental number line (e.g., Dehaene et al., 1993; Hubbard et al., 2005). Such mappings are robust across a wide range of tasks and cultures, suggesting that spatial representations play a fundamental role in numerical cognition (Fischer & Shaki, 2015). However, despite extensive empirical research, a theoretical issue remains unresolved: namely, the extent to which SNAs are biologically constrained versus shaped by experience-dependent learning processes.

Evidence from non-human animals including chicks and 8-month-old human infants suggests that early-developing spatial biases may provide an initial basis for SNAs (Rugani et al., 2015; Bulf et al., 2016). Moreover, cross-cultural research demonstrates that the directionality of SNAs varies systematically with cultural experiences, most notably writing direction (Shaki et al., 2009). These findings have led to the view that SNAs are neither fixed nor purely innate but instead constitute flexible representations that are progressively tuned through interactions between early-developing spatial predispositions and culturally acquired conventions such as literacy (Nuerk et al., 2015; Zebian, 2005).

Evidence for cultural modulation of SNAs was first provided by the SNARC (spatial-numerical association of response codes) effect. Dehaene et al. (1993) demonstrated that French adults responded faster with the left hand to smaller numbers and with the right hand to larger numbers, consistent with a left-to-right mental number line shaped by literacy experience. Notably, this effect was absent in a group of Iranian immigrants, whose participants had heterogeneous linguistic and literacy backgrounds, including a right-to-left writing culture, suggesting that exposure to specific writing conventions plays an influential role in modulating SNAs. Subsequent studies focusing on native speakers of right-to-left writing cultures have indeed exhibited a reversed, right-to-left SNARC effect (Shaki et al., 2009).

Cultural influences on SNAs have also been found in more explicit spatial tasks, such as ordering and counting. Shaki et al. (2012) showed that British adults preferred left-to-right counting, whereas Palestinian adults preferred right-to-left counting, indicating the dominant writing direction of their respective cultures. Although these findings suggest an interaction between early-developing spatial predispositions and culturally structured experiences, most evidence comes from adult populations, and the developmental processes through which such culturally specific SNAs emerge remain largely unknown. In particular, cross-sectional studies tracing SNAs across a broad developmental span are scarce. Moreover, recent evidence from non-industrialized populations with limited exposure to formal schooling and directional literacy practices systematically mapped numbers and other magnitudes onto space but showed no consistent directional bias (Pitt et al., 2021).

Furthermore, most research on SNAs has focused mainly on horizontal mappings, particularly left-to-right associations shaped by writing direction (Dehaene et al., 1993; Nuerk et al., 2015; Shaki et al., 2009). While these studies provide strong evidence for cultural modulation of SNAs, horizontal mappings often align with early-developing spatial predispositions observed in infants and non-human animals, making it difficult to disentangle the respective contributions of biological predispositions and cultural experiences (Rugani et al., 2015; Bulf et al., 2016). In contrast, vertical SNAs offer a theoretically informative test case. Previous

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studies in English-speaking 5- to 7-year-old children and adults suggest a default bottom-to-top association between numerical magnitude and vertical space (Cooney et al., 2021; Holmes & Lourenco, 2012). However, in cultures that employ top-to-bottom writing, such as Japanese and Cantonese, vertical reading conventions may conflict with these early-developing spatial predispositions. Therefore, examining how vertical SNAs emerge and change across development provides a useful opportunity to examine when and how experience-dependent learning reconstructs initial SNAs.

The present study aimed to examine the developmental mechanism through which culturally specific literacy-related experiences shape SNAs. Utilizing the Japanese writing system, which employs both horizontal (left-to-right) and vertical [1] (top-to-bottom) directions, we investigated how horizontal and vertical SNAs emerge and change across early development.

In Study 1, we focused on Japanese-speaking children aged 2 to 7 years and adults to investigate age-related changes in SNA directionality using card-ordering, counting, and sticker-placing tasks presented in both directions. We predicted that horizontal SNAs would be observable by approximately 4–5 years of age, given the use of an explicit task which places greater cognitive demands than implicit measures. Therefore, such biases may require additional developmental time before predisposed directional biases are reliably expressed. This prediction is consistent with prior work showing a reliable left-to-right bias in preschoolers of this age when performing object-counting tasks (Santiago et al., 2026). In contrast, we predicted that vertical top-to-bottom SNAs would be observed in older children as they gain more experience with vertically written Japanese.

In Study 2, we aimed to test more directly whether exposure to the Japanese writing system contributes to the modulation of SNAs, beyond age-related change. Although Study 1 examined developmental shifts in SNA directionality, such shifts could in principle be influenced by other culturally transmitted practices such as counting routines or observation of adults' spatial behaviors. To isolate the contribution of literacy-related experience, we used hiragana character-sound knowledge as an index of children's exposure to Japanese print. Japanese uses multiple writing systems, including kana (hiragana and katakana) and kanji. Hiragana is typically the first writing system acquired by Japanese-speaking children and is often learned through vertically organized materials, such as "gojūon" (hiragana 50-sound) tables and vertically written picture books. We predicted that greater knowledge of character-sound correspondence would be associated with a stronger top-to-bottom vertical SNA, even after controlling for age and nonverbal intelligence. In contrast, because horizontal SNAs in Japanese align with early-developing spatial predisposition, we predicted a weak or no association between hiragana character-sound knowledge and horizontal SNA directionality.

Study 1

Methods

Participants

A total of 202 children and 77 adults (74 females), all native Japanese speakers, participated in the study. The children's group included 15 2-year-olds (9 girls), 24 3-year-olds (13 girls), 30 4-year-olds (16 girls), 36 5-year-olds (14 girls), 41 6-year-olds (20 girls), and 56 7-year-olds (24 girls). This study was approved by the Research Ethics Committee of NTT Communication Science Laboratories, and written informed consent was obtained prior to the experiment.

Materials and Procedure

The sticker-placing task was first performed to avoid SNA-related bias. The order of the other two tasks (card-ordering and counting tasks) was counterbalanced. Each participant completed all tasks once.

Card-ordering Task Based on Eccher et al. (2025), participants were required to arrange stimuli varying in numerosity (1-4 random dots). They arranged white circle cards, each displaying a random dot configuration within a rectangular frame. The rectangular frame was oriented horizontally or vertically, resulting in two arrangement conditions. The use of a rectangular frame differs from the original procedure used by Eccher et al. (2025). The circle cards were 0.5 cm in diameter and displayed dots in a random configuration. Although Eccher et al. (2025) used 1 to 10 dots, we used 1 to 4 dots to include younger toddlers.

Counting Task Following Shaki et al. (2012), participants were asked to count aloud the printed circles (each 4 cm in diameter) on an A4 sheet as they touched each one. This task consisted of horizontal and vertical alignment conditions, and the order of counting was recorded. To capture their spontaneous SNAs, no demonstration was given to avoid experimenter-induced directional bias.

Sticker-placing Task The sticker-placing task was administered not to capture SNAs, but to assess visual/motor directional preferences independent of numerosity. Participants were asked to place one sticker in each of four circles, which had the same design as those used in the counting task. The task was also performed both vertically and horizontally.

Statistical Analysis

Directionality scores were quantified using the Kendall Tau correlation coefficient, as described by Pitt et al. (2021) and Eccher et al. (2025). For each task of horizontal and vertical directions, the arrangement for each participant was correlated with the ideal arrangement. In the horizontal direction, the ideal arrangement was set at 1-2-3-4 from left

[1] We used "vertical" to refer to the near-far direction in the two-dimensional space. This direction is sometimes referred to as the "sagittal" in the SNA studies examining three-dimensional directionality.

to right, indicating complete left-to-right directionality if they responded in the 1-2-3-4 order, and the coefficient would be 1. In contrast, if they showed complete right-to-left directionality, the coefficient would indicate −1. Thus, the positive coefficient (+) indicates left-to-right and the negative coefficient (–) indicates right-to-left directionality. The absolute value reflects the degree of consistency in the ordering. The same logic was applied to the vertical condition, with 1-2-3-4 defined from top to bottom, suggesting a positive coefficient for top-to-bottom and a negative coefficient for bottom-to-top. Statistical analyses were conducted using RStudio (Version 2024.04.1) and R (version 4.4.0).

Results

Figure 1 illustrates the distribution of directionality scores (Kendall's Tau correlation coefficient) for each task of horizontal and vertical direction. The colored distributions represent participants' responses for each age group. Each distribution differed significantly from the chance distribution (grey), suggesting that participants understood the task and did not respond randomly (two-tailed two-sample Kolmogorov-Smirnov test: all *ps* < .001). This trend was also supported by Pearson's correlation between mapping direction scores across tasks. In both horizontal and vertical conditions, all correlations were significant (Table 1), suggesting that directionality scores were consistent across tasks and that participants responded in a consistent manner across tasks.

Table 1: Correlations of mapping direction across card-ordering, counting, and sticker-placing tasks in horizontal and vertical conditions.

	Card-ordering	Counting	Sticker-placing
Horizontal			
Card-ordering	—		
Counting	.253***	—	
Sticker-placing	.213**	.279***	—
Vertical			
Card-ordering	—		
Counting	.353***	—	
Sticker-placing	.424***	.534***	—

*** $p < .001$, ** $p < .01$

Next, we examined direction biases: the dots and whiskers in Figure 1 show means and ±1 standard deviation (SD), with a grey dashed line indicating no directional bias. In the horizontal direction, a two-tailed one-sample Wilcoxon signed-rank test revealed a significant left-to-right bias in 5-year-olds in card-ordering and sticker-placing tasks (all *ps* < .01; Holm-corrected). Additionally, a significant left-to-right bias was observed in participants aged 6 and above in the counting task. In the vertical direction, a significant top-to-bottom bias was found from age 7 onward in card-ordering and counting tasks, and in the sticker-placing task in adults (*ps* < .001). In contrast, a significant bottom-to-top bias was observed in 3-year-olds in the counting task.

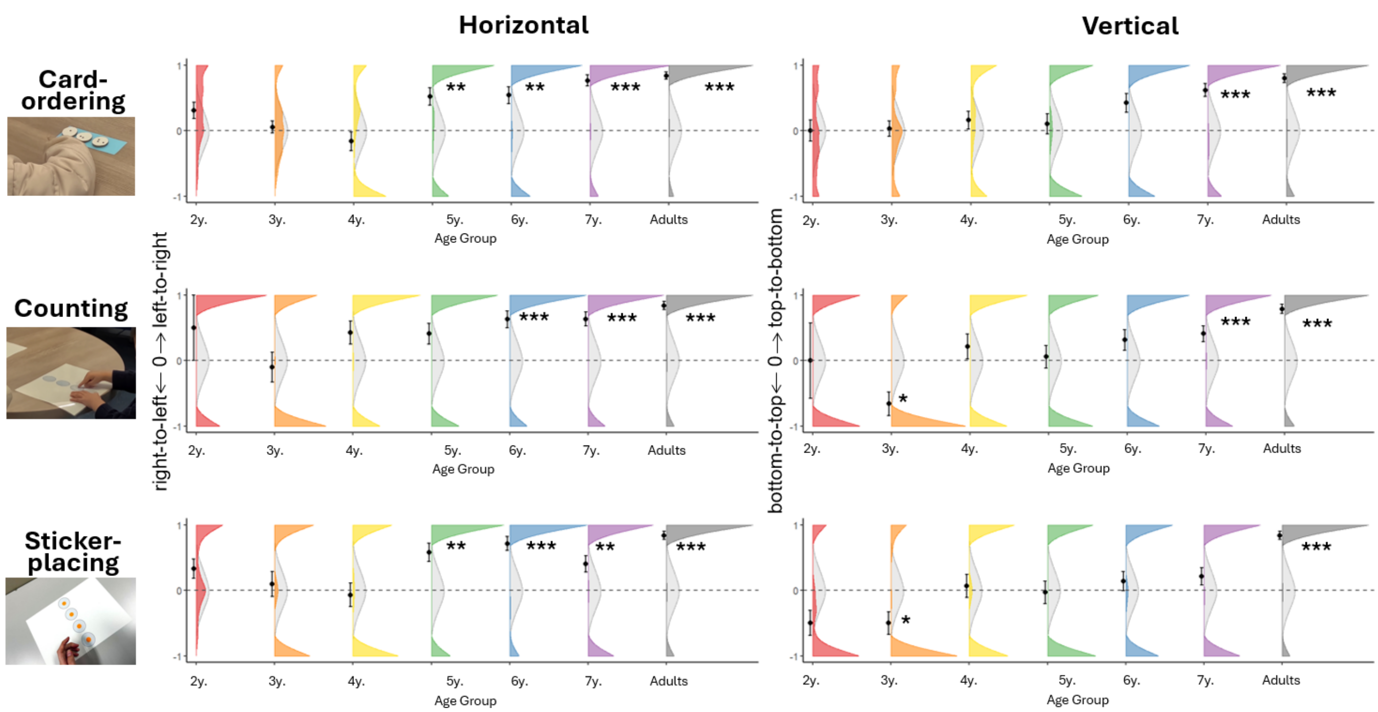

Figure 1: Directionality of alignment for card-ordering, counting, and sticker-placing tasks on horizontal and vertical conditions. The directionality score was calculated for each participant using the Kendall Tau coefficient; a positive value indicated left-to-right bias for horizontal directions and top-to-bottom bias for vertical directions. Observed distributions were significantly different from a random distribution shown in grey. Black dots and whiskers showed the mean directionality score and ±1 standard deviation. Statistical significance of directionality was observed by the two-tailed Wilcoxon signed rank test (* $p < .05$, ** $p < .01$, *** $p < .001$; Holm-corrected)

Discussion

In Study 1, we aimed to clarify the developmental changes in vertical and horizontal SNAs in Japanese-speaking children and adults exposed to both vertical and horizontal writing directions. Horizontal SNAs showed a left-to-right pattern after age 5, consistent with previous findings in Western cultures (e.g., Dehaene et al., 1993). In contrast, vertical SNAs showed distinct developmental patterns. Although previous studies of Western adults have reported a bottom-to-top SNA, Japanese-speaking children aged 7 years and older exhibited a top-to-bottom SNA in the card-ordering task. This pattern was particularly evident in the counting task: while younger children showed either a bottom-to-top tendency or no reliable directional bias, a reliable top-to-bottom directionality emerged after 7 years of age. This result suggests that SNAs can be modulated by culturally specific literacy-related experiences.

The present results are consistent with previous findings suggesting that cultural experience contributes to SNAs (e.g., Shaki et al., 2012). For vertical SNAs, Göbel (2015) showed that Cantonese-speaking 4- to 5-year-olds exposed to a vertical writing system exhibit a top-to-bottom directionality. The present study extends these findings by showing bottom-to-top directionality at age 3. This finding should be interpreted with caution, as the children at 4 years did not show bottom-to-top directionality; however, bottom-to-top directionality at 3 years may provide insight into developmental changes in SNAs. Despite this clear directionality bias in the card-ordering and counting task, no significant top-to-bottom bias was found in the sticker-placing task in children. The absence of a reliable top-to-bottom directionality bias in the sticker-placing task among children suggests that vertical SNAs cannot be solely explained by general motor or visuospatial preferences.

Study 2

The findings from Study 1 revealed developmental changes in SNAs, which are presumably driven by culturally specific literacy-related (i.e., print-based) experiences. However, further investigation is needed to examine the role of exposure to writing systems in shaping SNAs, which we address in Study 2.

Methods

Participants

A total of 109 Japanese-speaking children, 16 5-year-olds (7 girls), 38 6-year-olds (18 girls), and 55 7-year-olds (24 girls), participated in this study. The sample partially overlapped with that of Study 1, as the data for both studies were collected during the same testing session. The age range was restricted to better capture the effect of exposure to writing systems. An additional 7 children were removed for failing to complete all the tasks.

Materials and Procedure

The order of each task was counterbalanced.

Card-ordering and Counting Tasks These two tasks were conducted using the same method as Study 1.

Hiragana Character-sound Task Participants were presented with Hiragana characters on a tablet and required to produce the corresponding sounds without time pressure. There were 104 stimuli in total, including *seion* (e.g., 'あ' /a/), *dakuon* (e.g., 'ば' /ba/), *handakuon* (e.g., 'ぱ' /pa/), and *youon* (e.g., 'きゃ' /kya/)[2]. The number of correctly identified characters was counted as the score (Figure 2).

Figure 2: Hiragana character-sound task

Non-verbal Intelligence Task The Raven's Colored Progressive Matrices **(**RCPM) was administered to measure nonverbal intelligence, comprising three test sets (Sets A, AB, and B). However, because it was too redundant for children to complete all sets, sets A and AB were administered, consisting of 24 items. The children were asked to choose the missing element from six drawings by stating the number of items or pointing, allowing for task administration without verbal expression. The number of correct answers was recorded as the score.

Statistical Analysis

Logistic regression analyses were conducted separately by direction (horizontal vs. vertical) and task type (card-ordering vs. counting), resulting in four models. As most of the children showed complete directionality (Table 2), such as 1-2-3-4 from left-to-right, and thus children who did not demonstrate complete directionality (i.e., no direction in Table 2) were excluded. Directionality served as the dependent variable, with age in months, hiragana character-sound score, and RCPM score as predictors.

Table 2: Number of children who indicate a specific direction.

	Card-ordering	Counting
Horizontal		
Left-to-right	87	85
No Direction	7	1
Right-to-left	15	19
Vertical		
Top-to-bottom	73	70
No direction	9	1
Bottom-to-top	27	35

[2] Strictly speaking, *youon*— one mora sound consisting of two characters— is not a character. However, *youon* is simply mapped onto sound without meaning, as in the letters in the alphabet. Thus, we use "character-sounds" for clarity.

Results

Table 3 shows the results in the horizontal and vertical conditions. In the horizontal condition, neither the card-ordering nor the counting tasks revealed significant predictors for directionality (all ps > .10), suggesting a null effect of hiragana character-sound ability for horizontal directionality.

In the vertical condition, the results of the card-ordering task showed that both age (OR = 1.27, 95% CI [1.08–1.57], $p < .01$) and hiragana character-sound knowledge (OR = 1.13, 95% CI [1.02–1.31], $p < .05$) were positively associated with a top-to-bottom preference, indicating that older children and those with higher character-sound knowledge were more likely to arrange the numerosities from top to bottom. A statistically significant but very small interaction effect between age and hiragana character-sound knowledge was also found (OR = 1.00, 95% CI [1.00–1.00], $p < .05$). In the counting task, there was a marginal, non-significant effect of hiragana character-sound knowledge, suggesting that higher hiragana character-sound knowledge was weakly associated with a tendency to count from top to bottom ($p < .10$).

Discussion

The present study aimed to test whether exposure to print-based writing conventions modulates the directionality of SNAs by examining the relationship between hiragana character-sound knowledge and SNAs in Japanese-speaking children aged 5 to 7 years, who are exposed to a writing system that includes vertically oriented text.

In horizontal conditions, no significant effects of age, nonverbal intelligence, or character-sound knowledge were observed for either task. This suggests that character-sound knowledge does not contribute to horizontal SNAs, which is consistent with the left-to-right direction of horizontal writing in Japanese.

In the vertical condition, higher hiragana character-sound knowledge was associated with a top-to-bottom directionality in the card-ordering task. Japanese-speaking children are exposed to a top-to-bottom writing direction, particularly when explicitly learning hiragana characters. Therefore, we interpret hiragana character-sound knowledge as an index of children's exposure to vertically oriented Japanese writing conventions. This finding suggests that exposure to top-to-bottom writing conventions may contribute to the developmental reorganization of vertical SNAs. This interpretation is further supported by the fact that hiragana character-sound knowledge remained a significant predictor after controlling for age.

General Discussion

The present study investigated how cultural literacy-related experience shapes the developmental organization of SNAs by examining horizontal and vertical mappings in Japanese-speaking children and adults. Study 1 demonstrated that in Japan, where both vertical and horizontal writing systems are employed, left-to-right horizontal SNAs are expressed from the preschool years onward, consistent with patterns commonly reported in Western cultures. In contrast, top-to-bottom vertical SNAs are observed in school-aged children and older individuals, suggesting that such directionality emerges with increased exposure to top-to-bottom written text. Study 2 further demonstrated that this developmental pattern was closely associated with the acquisition of hiragana character-sound knowledge. Together, these findings suggest that SNAs are not static reflections of fixed spatial biases but are developmentally reorganized through cultural literacy-related experience. In line with previous work, the present findings reinforce the view that SNAs are shaped by an interaction between early-developing spatial predispositions and culturally learned conventions such as reading and writing direction (e.g., Bulut et al., 2025; Nuerk et al., 2015).

To our knowledge, this is the first study to demonstrate a robust association between the acquisition of hiragana character-sound knowledge and the directionality of SNAs. Previous cross-cultural research has demonstrated that SNAs vary systematically across cultures (e.g., Shaki et al., 2012; Göbel, 2015), and these differences have often been attributed to the directionality of writing systems. However, cross-cultural comparisons alone make it difficult to disentangle the effects of writing direction from other culturally shared conventions, such as general directional preferences or motor routines (e.g., Bulut et al., 2025). By examining character-sound knowledge within a single linguistic and cultural context and across development, the present study addresses this limitation and identifies literacy-related experiences as a proximate mechanism through which cultural conventions shape SNAs.

The present findings support the view that SNAs are not fixed mappings but flexible representations that are progressively tuned through cultural experiences. These

Table 3: Results of regression analysis in horizontal and vertical conditions.

	Horizontal				Vertical			
	Card-ordering (n=102)		Counting (n=104)		Card-ordering (n=100)		Counting (n=105)	
	OR	95%CI	OR	95%CI	OR	95%CI	OR	95%CI
Age (months)	.96	.80–1.13	1.10	.94–1.29	1.27**	1.08–1.57	1.08	.95–1.24
Hiragana	.97	.85–1.08	1.03	.92–1.14	1.13*	1.02–1.31	1.08	.99–1.20
RCPM	1.00	.81–1.21	.96	.80–1.13	.91	.76–1.08	1.08	.95–1.2 4
Age × Hiragana	1.00	1.00–1.00	1.00	1.00–1.00	1.00*	1.00–1.00	1.00	1.00–1.00

Abbreviation: RCPM, Raven's Colored Progressive Matrices. *$p < .05$, **$p < .01$.

findings suggest that early-developing predispositions are reinforced through development and become robust enough to be observed in explicit tasks. Crucially, the Japanese writing system, which incorporates two orthogonal writing directions (horizontal and vertical), provides a unique natural experiment for examining how print-based experience reorganizes spatial-numerical mappings in a direction-specific manner. The present findings extend existing models of SNAs by demonstrating that different spatial mappings (horizontal vs. vertical) can follow distinct developmental trajectories within the same individuals, depending on the alignment or conflict between early spatial biases and cultural conventions.

The timing of the emergence of directionality bias further supports a literacy-based account of SNA reorganization. Vertical top-to-bottom SNAs emerged around age 7, coinciding with the period during which most Japanese children begin formal reading instruction and acquire fluency in vertically written materials such as picture books, textbooks, and drills. This temporal correspondence suggests that the observed pattern is unlikely to be explained by maturation or general cognitive development. Consistent with this interpretation, logistic regression analyses showed that hiragana character-sound knowledge, but not nonverbal intelligence as measured by the RCPM, predicted the directionality of vertical SNAs. Together, these findings provide converging evidence that cultural literacy-related experience plays a specific role in restructuring SNAs.

Beyond numerical cognition, the present study has broader implications for understanding the interaction between culture, cognition, and development. SNAs represent a domain in which culturally transmitted practices leave measurable traces on fundamental mental representations. The presence of directionality bias in the card-ordering task, as demonstrated by the present findings, shows that cultural learning does not merely add surface-level strategies but can also reorganize the directional structure of core cognitive mappings. Moreover, the Japanese writing system offers a valuable test case for theoretical models of SNAs that assume bidirectional or multidimensional spatial representations, demonstrating that the human cognitive system can flexibly integrate multiple spatial frames depending on learned conventions.

Several limitations should be acknowledged. First, although the present study employed a developmental sample ranging from early childhood to adulthood, the design was primarily cross-sectional. Longitudinal studies are needed to confirm individual developmental trajectories of SNA reorganization. Second, the present study focused on behavioral measures of directionality rather than underlying neural mechanisms. A recent study has suggested that early horizontal SNAs may be rooted in hemispheric asymmetries, with the right hemisphere preferentially processing lower magnitudes and the left hemisphere higher magnitudes (Felisatti et al., 2020). Future neuroimaging studies could clarify how literacy experience modifies the neural substrates of SNAs. Third, SNAs can be expressed implicitly or explicitly (Eccher et al., 2025). The present study relied on tasks that explicitly link number and space; extending this work to implicit measures across development remains an important challenge. Finally, because the present study was conducted exclusively in Japan, further cross-cultural studies are needed to assess the generality of the present findings.

In conclusion, the present research provides new evidence that literacy-related experience modulates the developmental organization of SNAs. In Japan, left-to-right horizontal SNAs, which are thought to be consistent with spatial predisposition observed in infancy, are expressed before schooling, reflecting an alignment between early spatial predisposition and cultural experiences. In contrast, top-to-bottom vertical SNAs emerge after schooling as children acquire literacy skills in vertically written Japanese. By combining developmental methods with the unique cultural contexts of a bidirectional writing system, the present study demonstrates that emergent literacy-related experience is not merely a linguistic achievement but a transformative cultural experience that reshapes fundamental cognitive mappings between space and number.

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