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Number Prompts Left-to-Right Spatial Mapping in Toddlerhood

Koleen McCrink, **Jasmin Perez**, and **Erica Baruch**

Barnard College, Columbia University

Abstract

Toddlers performed a spatial mapping task in which they must learn the location of a hidden object in a vertical array, and transpose this location information 90° to a horizontal array. During the vertical training, they were given a) no labels, b) alphabetical labels, or c) numerical labels for each potential spatial location. After the array was transposed to become a horizontal continuum, the children who were provided with numerical labels during training, and those children who heard alphabetical labels and formed a strong memory for the vertical location, selectively chose the location corresponding to a left-to-right mapping bias. Children who received no concurrent ordinal labels during training were not able to transpose the array, and did not exhibit any spatial directionality bias after transposition. These results indicate that children exhibit more-flexible spatial mapping compared to animals, and this mapping is modulated depending on the type of concurrent ordinal information the child receives.

Keywords

space; number; order; counting; labels; toddlers

The relationship between space and number is a privileged one; it has been studied from the early days of psychological inquiry (Galton, 1880) and crystallized into the popular conception of a mental number line (Moyer & Landauer, 1967). In a seminal study, Dehaene, Bossini, & Giraux (1993) found that French-speaking adults associate small numbers with the left side of space, and large numbers with the right. This asymmetric mapping is not exclusive to spatial-numerical associations, and its presence for many types of stimuli that are ordinal (e.g., have a defined sense of commencement and finality) indicates that a more accurate term is that of spatial-ordinal associations. Spatial biases have been found for such varied stimuli as months of the year/days of the week (Gevers, Reynvoet, & Fias, 2003, 2004), letters of the alphabet (Gevers et al., 2003), pitches of sounds (Rusconi, Kwan, Giordano, Umilta, & Butterworth, 2006), and newly ordered random word sequences (Previtali, de Hevia, & Girelli, 2010; Van Opstal, Fias, Peigneux, & Verguts, 2009). For example, adults who are given a list of nouns to encode in a particular order (e.g., "bow", then "tent", then "apple"), go on to exhibit a spatial bias in which they respond more quickly to early-appearing words with the left side, and late-appearing words with the right side (Previtali et al., 2010).

Correspondence concerning this article should be addressed to Koleen McCrink, Department of Psychology, Barnard College of Columbia, 3009 Broadway, New York, NY 10027. kmccrink@barnard.edu.
Koleen McCrink, Assistant Professor of Psychology, Barnard College of Columbia University.

Spatial-ordinal relationships are influenced by evolutionary factors, as well as the culture and language of the participants. Work on special populations with little or no interactive experience with the world (e.g., newly hatched chicks, human infants) has documented an untrained and spontaneous propensity to map quantitative information to a spatial continuum. Experimentally naïve young chicks (*gallus gallus*), trained to find food at the 4th location from the bottom in a vertical array, will selectively go to the 4th location from the left when that array is surreptitiously transposed 90 degrees, indicating a spatial bias to start their search for food on the left and progress towards the right (Rugani, Kelly, Szelest, Regolin, & Vallortigara, 2010). (This same phenomenon has recently been documented in monkeys (*macaca mulatta*: Drucker & Brannon, 2014), though these animals are older and have extensive experience with their human caretakers.) Further, chicks trained to peck a centrally presented panel displaying an intermediate number of dots (e.g., 8), are subsequently more likely to orient to a left-side panel display of a small number of dots (e.g., 2) than a right-side small-number display, a behavior that suggests conceptual congruency for small/left and large/right associations and may reflect an innately asymmetric mental number line (Rugani, Vallortigara, Priftis, & Regolin, 2015). This innate asymmetry is proposed to be driven by right-hemisphere dominance of spatial-attentional processing, which causes chicks to start their search with a left spatial bias (Vallortigara, 2012).

Work by de Hevia and colleagues (Bulf, de Hevia, & Macchi-Cassia, 2015; de Hevia, Izard, Coubart, Spelke, Streri, 2014; de Hevia & Spelke, 2010; de Hevia, Vanderslice, & Spelke, 2012) has also documented an early-developing propensity in human infants to link numerical and spatial information (as well as temporal; see also Lourenco & Longo, 2010). There is evidence that the linkage between space and number may be asymmetrically oriented in this naïve population as well; infants learn to order a set of arrays if they are presented from smallest on the left to largest on the right (de Hevia, Girelli, Addabbo, & Macchi-Cassia, 2014), but not vice versa, and are quicker to attend to a left-side probe after central presentation of a small number vs. central presentation of a large number (Bulf, de Hevia, & Macchi-Cassia, 2015). According to this view, the evolutionarily-based bias to start a visual scan with the left side of space is paired with a bias to prefer sequences that increase in magnitude (de Hevia, Addabbo, Girelli, & Macchi Cassia, 2014), and this gives rise to the lateralized processing of number seen in Bulf et al. (2015).

Evolutionary factors do not have exclusive rights to the nature of these spatial biases; there is also evidence that the surrounding culture of the participant modulates the directionality of the initial-final mapping. Adults enculturated to a right-to-left reading and writing system experience attenuated or reversed spatial-numerical mappings (Dehaene et al., 1993; Shaki, Fischer, & Petrusic, 2009), and illiterate adults do not exhibit asymmetric spatial biases at all (Zebian, 2005). Cultural modulation is found for more generic spatial-ordinal biases as well (Shaki & Gevers, 2011; Shaki, Petrusic, & Leth-Steensen, 2012; Vallessi, Weisblatt, Semenza, & Shaki, 2014). Vallesi, Weisblatt, Semenza, and Shaki (2014) found attenuated left-short and right-long, spatial-temporal mappings in Israeli participants (whose language is written from right-to-left) relative to Italian participants (whose language is written from left-to-right). Further, Shaki and Gevers (2011) presented bilingual Hebrew-English speakers with letter sequences in either the English alphabet (read from left to right) or Hebrew alphabet (read from right to left). These bilinguals exhibited both left-to-right and right-to-left spatial mapping biases, depending on the language used in that block of the experiment. This cultural influence is evident by three to four years of age; preschoolers are more likely to use numerical and alphabetical labels to solve a spatial reasoning task if they are presented in a culturally consistent direction (McCrink, Shaki & Berkowitz, 2014; Opfer & Furlong, 2011; Opfer, Thompson, & Furlong, 2010).

What, then, are the specific cultural influences responsible for modulating the direction of children's spatial biases? One candidate, explored in the current study, is the child's burgeoning knowledge of linguistic labels. The cultural modulation found by previous researchers is thought to be driven, directly (Dobel et al., 2007; 2014; Tversky et al., 1991; Tversky, 2010) or indirectly (McCrink et al., 2016; Patro, Nuerk, & Cress, 2016), by the left-to-right or right-to-left nature of the scripted language that dominates the participant's daily life. Therefore linguistic labels are a natural area of study for looking at early cultural influences at this developmental juncture. Further, different sorts of ordinal labels allow one to observe the relative influence of highlighting attention to quantitative dimensions (e.g., exact number labels), as compared to *non-quantitative* dimensions (e.g., letters of the alphabet), on spatial representations. Attention to labels helps toddlers form abstract representations of how to solve a problem (Ratterman & Gentner, 1998), especially when that problem involves inhibitory control or executive functioning abilities (Kirkham et al., 2003; Miller & Marcovitch, 2011; Muller, Zelazo, Hood, Leone, & Rohrer, 2004, but see Miller, Marcovitch, Boseovski, & Lewkowicz, 2015; Muller, Zelazo, Lurye, & Liebermann, 2008). One relevant model – the hierarchical competing systems model (HCSM; Marcovitch & Zelazo, 2009) – posits that spatial search tasks are solved via the use of two systems: a habitual response system and a representational system. Sometimes these systems experience congruency (as when an object is hidden in the same location), but often they are in conflict (such as when an object's location must be updated). The use of labels helps the child strengthen their representation of the location of the item, when they can no longer rely on their habitual response. The additional representational layer of a label allows for re-processing, reflection, and a subsequently increased conscious awareness and representational trace in memory (The Levels of Consciousness framework of Zelazo & Zelazo (1998)). Within the context of a spatial search task, different sorts of labels may lead to distinct biases when reprocessing, or reflecting upon, location representations.

Toddlers are a telling population in that they are beginning to point, to ask for labels and elicit labels themselves, and readily repeat counting sequences by rote memory in addition to learning how to sing the alphabet song (Schaeffer, Eggleston, & Scott, 1974; Suortti & Lipponen, 2016; Wynn, 1992; Zelazo, 2004). Recall, also, that toddlers are of an age just before one observes sensitivity to cultural influences in moderating their spatial biases (McCrink et al., 2014; Opfer et al., 2010). In order for young children to learn from their given culture, they must be cognitively flexible and readily accepting of the verbal and non-verbal structure adults and caregivers impose upon their world. These are pedagogical aspects that begin in infancy (McCrink, Birdsall, & Caldera, 2011; McCrink, Caldera, & Shaki, 2016), and via the use of language, gesture, and pictures continue throughout childhood (Tversky, 2011; Tversky, Kugelmass, & Winter, 1991). Toddlers are on the brink of full enculturation; they provide a test case of how we bridge innate spatial biases observed in infancy and the lifelong implications of spatial enculturation.

In the current study, we adapt the navigational paradigm used by Rugani and colleagues (Rugani et al., 2010, 2011) for use with human toddlers. These toddlers are exposed to differing levels of explicit ordinality while learning about the spatial location of an object in an array, receiving either a) no labeling information (an experimental setting akin to that found in the non-human animal studies), b) ordinal but *not* numerical information (letters, to investigate whether an ordered sequence, but not quantity, drives spatial asymmetry), or c) numerical information (numbers, to provide toddlers with a sense of magnitude as well as ordinality). With respect to overall performance, if labeling allows for greater representational strength (as found by Miller & Marcovitch, 2011), we should observe overall better location learning during training, and more-accurate spatial mapping after transposition, for the Labeled conditions compared to the Unlabeled condition. This benefit need not have a directional component, since transposition from a vertical to horizontal array has two correct possible answers. With respect to directionality of the mapping process, the strongest versions of the evolutionary account and the enculturation account make differing predictions. If asymmetric visuo-spatial processing is consistently found throughout development (as would be predicted by the evolutionary account), one would find evidence for asymmetric left-right mapping irrespective of the presence of ordinal labels during training. These US children have received no consistent counter-evidence to their preexistent bias to associate initial stimuli with the left side of space, and final with the right side. If spatial asymmetry is solely culturally instantiated, and takes time and experience to develop, one would find weak or no asymmetric mapping during transposition, increasingly present as the children get older, or when the child has a) cues to conventional ordinality, and b) mastery of the structured ordinality of the count list or alphabet.

Method

Participants

200 two- and three-year-olds were recruited to participate at a local children's museum and in the local parks of a major urban area. 56 participants were excluded due to refusal to complete the task (28), a language barrier (1), experimenter error (erroneously mentally rotating the array and subsequently baiting the wrong box: 19), or exposure to a right-to-left oriented language (e.g., Hebrew, Arabic, or Farsi), as assessed by parental report on the consent form (8). The final sample of participants included 72 two-year-olds (24 months to 35 months, *m* = 30.4, 36 females) and 72 three-year-olds (36 months to 47 months, *m* = 40.6, 36 females). Sample size was based on other studies which use a toddler-friendly search task and one-trial test sequence (e.g., Feigenson & Carey, 2003). This protocol was approved by the Institutional Review Board of the authors' institution, and was conducted in accordance with the principles laid out in the World Medical Association Declaration of Helsinki.

Design

Each child was assigned to one of three conditions: unlabeled, alphabetical, or numerical. The unlabeled condition utilized instructions for the spatial mapping task without explicit lettering or numbering of the boxes, with the experimenter stating: “I’m putting the toy in this box” while gesturing to the baited box. The alphabetical and numerical conditions implemented explicit labeling when the experimenter noted where she hid the toy: “I’m putting the toy in Box D/Four.” In order to avoid the concern that our predominantly right-handed population would handle right-side boxes more when the array was presented horizontally, half the children saw the second box from the bottom of the array baited with the toy, and half the fourth box from the bottom.

Stimuli and Procedure

The stimuli for the spatial mapping task consisted of a 70 × 14 cm board, six hinged, unmarked wooden boxes 8 × 8 × 8 cm affixed equidistally from each other and from the edges of the board, and a small 7 cm diameter liquid-filled squeeze-ball. The stimuli for the counting task comprised three toy jacks, and the stimuli for the handedness check was a cartoon figurine. One additional box, used only for the first trial, was covered in stickers in order to attract the attention of the participants and increase the likelihood of attending to, and being rewarded at, the correct vertical location.

Warm-up and handedness check—Participants were first provided with a brief free-play session to “warm up”, in which they squeezed the ball and were allowed to play with the boxes, including an interaction in which the children were encouraged to practice opening the box and take out a toy. During this same warm-up period, the experimenter presented the figurine in a neutral position in front of the child and asked the child to take it; the hand used by the child was noted as their dominant hand. Children who used one hand on the choice task but a different hand on the counting task, or when opening their boxes, were coded as mixed-handed ($n = 7$ mixed; 28 left-handed; 109 right-handed).

Spatial mapping task—Participants were then given the spatial mapping task. The children were either seated with a caregiver, or independently on a chair, 30 cm away from the rug. The task was composed of four trials in total: three vertical trials during which children were scaffolded into mapping the toy to a certain box (unchanging within each child) in an array that was radially arranged with the first box closest to the child, and a single horizontal trial in which the array was surreptitiously transposed 90 degrees. (See Figure 1 for a schematic.) In the first trial, the experimenter positioned herself on the floor behind the board, which was radially oriented from the child. She opened each box individually, starting with the box closest to the participant. She stated if it was empty or baited while moving up the array, exclaiming, “Look! There is nothing in *this box* (unlabeled condition)/*box letter A* (lettered condition)/*box number 1* (numbered condition) … Nothing in *this box* (unlabeled condition)/*box letter B* (lettered condition)/*box number 2* (numbered condition)… Nothing in *this box* (unlabeled condition)/*box letter C* (lettered condition)/*box number 3* (numbered condition). Look! I’m hiding the ball in *this box* (unlabeled condition)/*box letter D* (lettered condition)/*box number 4* (numbered condition)! Nothing in *this box* (unlabeled condition)/*box letter E* (lettered condition)/*box number 5* (numbered condition).” The experimenter tilted the board slightly so that the participants were able to clearly see inside the empty boxes and the hiding of the ball in the target box. Then the board was placed back on the rug and the participants were asked, “Where is it? Can you find the ball?” and encouraged to search.

The second trial was identical to the first, with the experimenter repeating the same labeling script and toy-hiding placement, but the sticker box was replaced with an unmarked box, identical to the others on the board. In the third trial (final vertical transposition), the experimenter hid the ball without the participants seeing, and without providing a labeling script, turning the board neutrally away from the child and asking them to close their eyes, exclaiming “I am going to hide the ball without you looking, but I think you will know where it is!” The board was again vertically presented in a radial array fashion from the child, with the first location closest to the child. In the fourth and final trial (horizontal transposition), the experimenter again hid the ball while turned away from the participant, and then presented the board horizontally to the participants, again without providing a labeling script. The instruction to search was then given. Prior to retrieval for all trials but the first, the experimenter told the child, “Remember, I always hide the ball in the same box,” to ensure that children understood that each successive trial’s hiding location was identical to the first. During search, the experimenter knelt down and did not look at the child until the child had opened a box. For each trial, an experimenter to the side of and slightly behind the child coded their search locations by noting the first opened box and any subsequent boxes the child opened. A subset of the trials (25%) were coded by a researcher naïve to the hypotheses of the study; reliability was .94. A subset of the trials (~25%) were coded for the child’s first touch instead of first successful open; there were very few cases in which these measures were in conflict (~3%).

Counting task—The study concluded with a counting task modeled after Opfer et al. (2010). First the experimenter demonstrated how to point to, and count, one jack. Then, after setting up the three jacks in a horizontal line in front of the participant while the participant was not looking, she instructed the participant to point to and count the jacks. The coder recorded the directionality, or lack thereof, of the counting (left-to-right, right-to-left, or non-directional); the hand used to point to the jacks was also coded, to provide an additional measure of the child’s manual lateralization. Children who did not count all the jacks, or who counted the leftmost/rightmost, rightmost/leftmost, and then middle, were coded as having non-directional, disordered counting.

Coding—Because half the children saw the second box from the bottom baited, and half the fourth box from the bottom, we coded the children’s responses in terms of relative – and not absolute – position. For example, for children who saw the 2nd box farthest from them (e.g., from the bottom of the array) baited, and subsequently chose the 1st box from the left after transposition, this behavior was coded as “near-end”. The five potential location options were LR (the box chosen if one had a LR transposition bias, i.e., the fourth box from the left after learning the fourth box from the bottom was baited), RL (indicating a RL transposition bias, i.e., the second box from the left after learning the fourth box from the bottom was baited), middle, far-end (the box located at the end farthest away from the LR option), and near-end (the box located at the end nearest to the LR option.)

Results

Non-parametric chi-square analyses over the distribution of first-choice location for the horizontal test trial (LR, RL, middle, far-end, and near-end) as a function of age of child (2 years, 3 years) revealed no significant differences in choice across the two age groups for any of the locations or conditions (all $p_s > .05$). Thus all following results are collapsed across the variable of age. Children did not exhibit different levels of learning during the vertical training period as a function of condition (M = 1.7 Unlabeled, 2.0 Lettered, 1.8 Numbered, $F(2,141) = .87$, $p = .42$), an important metric to ensure that differing levels of interest/location learning are not driving differences at test. Furthermore, there were no significant effects of baited box, with overall responding to Box 2 at 25% and Box 4 at 33% ($F(1,143) = 1.20$, $p = .28$). Nor were there significant effects of handedness; of the 28 children judged to be left-handed, 4 chose Box 2, and of the 109 right-handed children, 27 chose Box 2 ($\chi^2(137) = 1.39$, $p = .24$). Eight of 28 left-handed children chose Box 4, and 28 of 109 right-handed children chose Box 4 ($\chi^2(137) = .10$, $p = .76$). These preliminary results indicate no significant effects of age, handedness, or side of the baited box.

Two-tailed exact binomial tests were used to determine whether each position was selected above a 1 out of 5 (20%) chance level by the children in each experimental condition. In the Unlabeled condition, children chose the middle position more frequently than chance (17/48, $p = .02$), and the near-end position less frequently (2/48, $p < .01$). In the Lettered condition, the children again chose the middle position more frequently than chance (16/48, $p = .04$), and the far end less frequently (3/48, $p = .03$). In the Numbered condition, children chose the LR position more frequently than chance (19/48, $p < .005$), and both end positions less frequently (3/48 near end, 4/48 far end, $p_s < .02, .05$). Figure 2 details the exact number of cases for each position. These results indicate a spike in middle position response for the Unlabeled and Lettered conditions, and LR position response for the Numbered condition.

Next we examine whether the relative distribution of LR vs. RL position choice differs by condition; that is, of the children who made an accurate mapping given their training, was this mapping according to a LR or RL strategy? Here we examine only children who chose the LR and RL locations, because these are the critical locations at which asymmetry would be potentially found after learning a correct vertical rule and accurately transposing. (Although some children may be responding to the LR or RL locations by chance, any truly random effects would exert equal influence across all three conditions.) When considering all children in the sample, it did not ($\chi^2(2) = 3.99$, $p = .13$). However, children who made a directional choice in the Numbered condition (that is, chose the second box in from the left or right) behaved significantly differently than children in the Lettered condition ($\chi^2 = 4.2$, $p = .04$) and marginally different from those in the Unlabeled condition ($\chi^2 = 2.93$, $p = .08$). These results indicate that children who were transposing successfully were relatively more likely to choose the LR mapping and less likely to choose the RL mapping (see Figure 2) in the Numbered condition relative to the other two conditions.

Because we did not train to criterion (a la Drucker & Brannon's (2014) monkeys and Rugani et al.'s (2010) chicks), it is possible that children who did not have a strong sense of the toy's position during vertical training would behave differently than the trained animals, for reasons that are not related to disparate spatial mapping tendencies, and instead reflect weaker spatial learning during training. To address this possibility, we performed an identical analysis of retrieval on the horizontal test trial, including only those children who were "good seekers" having successfully retrieved the toy during the third (final) vertical trial, in which the toy was hidden surreptitiously and the children needed to retrieve it from memory ($N = 25$, 21, and 28 for the unlabeled, lettered, and numbered conditions respectively). When considering this population, we do not observe a LR bias in the Unlabeled condition (the one most analogous to the animals, as they did not hear/see labels for the locations); the children continued to go to the middle box at a rate higher than chance (10/25, $p = .03$, two-tailed exact binomial test), avoided the near end box (0/25, $p < .01$), and showed chance responding to the other locations (2/25 far end, 5/25 RL, 8/25 LR). In this population of "good seekers", however, we observe a LR bias for *both* the Numbered and Lettered conditions. Children in the Numbered condition went to the LR box more often than chance (9/21, $p = .03$), avoided the ends (0/21 for both end types, $p = .02$), and went to the RL (5/21) and Middle (7/21) boxes at chance levels. Children in the Lettered condition went to the LR box more often than chance (11/28, $p = .03$), avoided the Far end (0/28, $p < .01$), and went to the RL (5/28), Middle (9/28), and Near end (3/28) at chance levels. Chi-square tests with one degree of freedom confirm that vertical prowess modulated horizontal LR choice exclusively for the Lettered condition (with 9 of 21 vertical learners, and just 2 of 27 vertical non-learners, going to the LR box: $\chi^2 = 8.40$, $p = .004$.) This set of results illustrates that children with a strong initial vertical mapping were more likely to transpose asymmetrically than those with a poor initial vertical mapping – but only for the Lettered condition.

Finally, we examined whether directional biases were influenced by the children's pre-existing spatial-numerical associations (SNAs), as measured by their counting tendencies. In our sample of 144 children, 79/144 exhibited a LR counting pattern (e.g. they started by pointing to the leftmost object, and ended with the rightmost object), 49/144 RL counting, and 16/144 non-directional/random counting. The choice behavior from the children in each condition who showed a LR ($n = 28$, 27, and 24 for the Unlabeled, Lettered, and Numbered conditions respectively), or RL ($n = 15$, 18, 16) counting system was analyzed using two-tailed exact binomial tests against chance (.2, for 1 of 5 possible boxes). (The non-directional counter prevalence was so low ($n = 5$, 3, 8) that, after considering response to all locations, the comparable statistics are not appropriate.) The only cells in which above-chance responding was observed were for the LR location, in the Numbered condition, with both LR (10/24, $p = .025$) and RL (7/16, $p = .05$) counters choosing this location at horizontal test at higher than chance levels. (See Table 1 for the exact percentage in each condition.) Chi-square tests with one degree of freedom were conducted to compare choice of LR or RL horizontal box as a function of counting directionality in each experimental condition; in each case there was no significant effect of the differing counting directionality (LR counters vs. RL counters). Taken together, these analyses illustrate that well-ordered counters were especially asymmetric – but only for the Numbered condition (see Figure 3; see also Supplementary Material - Table 1 for these data in percentage format).

Discussion

In the current study, toddlers were given a task in which they must transform vertical spatial knowledge to horizontal spatial knowledge. In non-human animals, this transposition is asymmetrical and occurs from left-to-right. We observe here no asymmetric spatial bias in the condition most closely resembling that used with animals; children who learned a vertical location without any additional information tended to “hedge their bets” and simply start their search with a neutral middle location. However, when numerical labels were added during vertical learning, these young children (even those with weak vertical location knowledge) exhibited an asymmetric bias to place initial stimuli on the left and final stimuli on the right. Other types of ordinal information – such as alphabetical labels for locations – moved children towards this asymmetric mapping as well, but in this case the children needed to have a strong vertical representation before transposition.

The asymmetric mapping bias documented here is multiply determined, with both strength of location knowledge and availability of conventional ordinal information as driving factors. Contrary to prior work (Opfer et al., 2010), we did not find that counting directionality had a significant overall impact on whether or not children mapped asymmetrically (e.g., that left-to-right counters in the Unlabeled condition would be more likely to spatially transpose with a left-to-right bias.) This effect only came about in the explicitly relevant numerical label condition, with directional counters of any type exhibiting left-to-right asymmetry. One possibility is that children need to possess directional counting abilities for a longer period of time in order for them to influence seemingly unrelated tasks (as in the unlabeled, or alphabetical, conditions); these children are much younger than those previously studied in directional SNA tasks, and are relatively new counters.

Children who had a strong representation of where the object was in the vertical array, transposed successfully and with a left-to-right bias – but only if they had additional ordinal information such as well-ordered labels. Otherwise, this effect was limited to the special case of number labels. Thus it appears that number is especially evocative of spatial asymmetry for these children. Exactly *why* it is evocative is an open question, and here we provide two potential explanations.

The first account emphasizes biological factors, and hinges on the work showing a right-hemisphere dominance that leads to left-initial spatial search (Rugani et al., 2010; Vallortigara, Regolin, Bortolomio, & Tommasi, 1996), in concert with an untrained pairing of small magnitudes with the left side of space and large with the right (Bulf et al., 2015; de Hevia et al., 2014; Rugani et al., 2015). According to this account, hearing the number words in the early part of the string activated the associated non-symbolic magnitudes (Benoit, Lehalle, Molina, Tijus, & Jouen, 2013; Negen & Sarnecka, 2011; Piantadosi et al., 2014), and the spatialized representations of these magnitudes led to a left-to-right scanning pattern. (Note that this is not a straightforward nativist account of baseline right-hemisphere spatial position encoding leading to left-to-right search; that account is ruled out by the lack of asymmetry in the Unlabeled condition.) This largely biological account is supported by the distinct lack of age differences; in no condition did it matter whether the child was 2 years of age or 3, despite 3-year-olds possessing fully 50% more knowledge and opportunity for enculturation than 2-year-olds. To empirically examine whether this is the most likely account, several follow-up studies are called for. One potential study would be use of a visual label (not a verbal label) to depict non-symbolic magnitudes on each of the locations during training, and see if explicitly viewing that non-symbolic quantity during encoding leads to the same asymmetric search pattern as that found here. Another way to test this account would be to administer a task that measures how well each child understands the mapping between the symbolic verbal label (“two”) and the non-symbolic quantity (an array of two dots) (Benoit et al., 2013; Condry & Spelke, 2008; Wynn, 1992), and then examine if the degree of aptitude in representing non-symbolic quantities via symbolic numbers is positively related to their search asymmetry.

The second account that describes why number labels prompt asymmetry is largely cultural, and takes into consideration the role of representational strength of the location for each condition (Miller & Marcovitch, 2011; Munakata, McClelland, Johnson & Siegler, 1997). In this account, three things must happen: the numerical labels enhance representational strength and memory trace (McCrink & Galamba, 2015; Miller & Marcovitch, 2011), the ordered nature of the labels prompts asymmetry (Gevers et al., 2003; Previtali et al., 2010), and the count list has special primacy as the most ordered of labels for these children. The first two parts of this account are documented in some form in the literature, but to our knowledge the third is not. It is possible that caregivers provide more order in a numerical labeling context than in any other context, and these children have been accustomed to shifting their gaze from left to right as they hear the count list. That is, an array of objects scattered in front of a child and their caregiver may be more likely to be labeled in order when invoking number concepts (“look! One… two… three… dolls.”) than, say, letter concepts (“Look! A doll. Doll starts with D.”).

Previous work has illustrated that English-speaking adults exhibit strong left-to-right pointing biases as they count (e.g. Shaki, Fischer, & Gobel, 2012). Thus this frequent recitation of the count list by caregivers may not only be especially well-ordered relative to other routines or labels, it may be especially directional as well. This caregiver-prompted asymmetry, in a numerical context, would explain the finding that children in kindergarten judge right-to-left or unordered counting routines to be incorrect, and strongly prefer left-to-right counting routines (Kamawar et al. (2010)). If the children here are accustomed to hearing the count list while objects are being pointed to (a situation which mimics the current paradigm), this heightens their representational strength of the scenario, and makes them more likely to use the labels to solve the transposition problem. When the children need to solve the transposition task, they cannot depend on their habitual response, and must lean on their representation of the scenario (Marcovitch & Zelazo, 2009). In the case of numbers, this representation has been inculcated in a left-to-right manner in their daily lives – even more so than other label types – and thus this is the manner in which they transpose.

As with the first account, this enculturation account of the present results is highly testable. One could observe and measure how often parents in different cultures provide directional structure via gesture in a numerical and non-numerical context (see McCrink et al., 2016), or calculate via a linguistic corpus such as the CHILDES database the conditional probability of the strings 1-2-3-4-5 vs. A-B-C-D-E. Further, one could also examine the behavior in an identical task of young toddlers in cultures where adults exhibit right-to-left counting routines (such as with Arabic speakers; Shaki et al., 2012). If there is a reversal of the pattern found here, enculturation is the prime driver of the effect. If there is no reversal, if there is an attenuation but not a full reversal, or if number is not especially ordinal in the day-to-day life of a child, then one must consider the possibility that low-level, innate biases for number to be spatially ordered are exerting an influence.

When reconciling these data with the comparative data from chicks (Rugani et al., 2010) and monkeys (Drucker, & Brannon, 2014), we must do so cautiously. The lack of asymmetric mapping in the Unlabeled condition from the current study does, at first glance, suggest that the spatial biases documented so readily in animals are not dominant in human toddlerhood. However, the current study has the very real limitation of comparing over-trained animals – who receive hundreds of trials – with toddlers who receive just three trials. One simply cannot overtrain children at this developmental stage. On a methodological level, they lose interest and refuse to participate in the critical test trial. On a theoretical level, over-training would not be a realistic view of how toddler learning occurs in the real world given their high levels of distractibility. This difference between training procedures for the two populations raises the possibility that these spatial biases may indeed be present in toddlers, but remain latent because their memory for the spatial location is very weak. The children's memory trace may be especially dampened in the Unlabeled condition because the assigned labels are generic (e.g., "this box"). On this account, number isn't prompting asymmetry – poor memory is masking latent spatial biases for the Unlabeled condition. However, we believe this alternate account for the difference between the chicks and toddlers is unlikely. First, the children learned the position of the object during training equally well in the Labeled and Unlabeled conditions, which would not be the case if generic labels dampened location memory. Even in the most difficult of training trials, in which the experiment hid the ball surreptitiously, performance was similar for both the Unlabeled and Labeled conditions. Second, when looking at only those toddlers who had a good sense of location before the transposition, the "good seekers" (a population that provides a neater parallel to the over-trained animal population), we still observe no asymmetric mapping in the Unlabeled condition.

In light of the lack of asymmetry in the condition most closely paralleling that of the animals, we believe that what is observed here is the burgeoning flexibility of humans. This flexibility arrives at a time where more than ever before children are becoming sensitive to the pedagogical and symbolic aspects of the environment around them: the rise of mimicry (Jones, 2007) and overimitation (Lyons, et al., 2007), the rich interpretation of social cues with caregivers (Gergely & Csibra, 2013), the fresh emergence of symbolic, verbal, and ordered labels such as the count list and alphabet (Schaeffer, Eggleston, & Scott, 1974; Suortti & Lipponen, 2016; Wynn, 1992; Zelazo, 2004). In surveying the literature, it becomes clear that toddlerhood must logically be the inflection point for the development of these spatial biases; infants show a distinct bias for left-to-right spatial mapping for discrete, countable objects (Bulf et al., 2015; de Hevia et al., 2014), but children around the age of 4 exhibit culture-specific spatial biases (McCrink et al., 2014; Opfer et al., 2010). Our theory posits that the flexibility in toddlerhood arises from agnosticism as to the directionality of the spatial biases, and heightened attentiveness to cultural norms.

According to this theory, if one could follow a group of children from infancy into toddlerhood, and test them on infant- and toddler-friendly versions of the same spatial tasks the propensity to show asymmetric spatial biases will be u-shaped, and not linear. Children's mapping strategy should move from a default left-to-right mapping, to an agnostic mapping that hinges in toddlerhood, to one that is culturally shaped. For example, one could implement an eye tracking study with infants, toddlers, and young children in which an object is hidden in a vertical array, and this array is surreptitiously transposed behind an occluder for a test trial. If this theory is correct, infants should exhibit shorter latency to orient to a revealed object at test that appears in a location congruent with a left-to-right mapping. Toddlers, on the other hand, should experience equally short latency to locations congruent with either a right-to-left or left-to-right mapping. Another test of this theory would be to implement in toddlers, young children, and older children the visual shift of attention method developed by Patro et al. (2016), in which moving an object across a screen rapidly inculcated spatial-numerical biases in 4-year-old children. If the theory we are advancing is correct, toddlers should be especially susceptible to externally provided directional cues relative to older children. Finally, an individual differences approach could be taken to test this theory; children who are the most sensitive to social norms (even those seemingly unrelated to space, or number) should be the population that is most responsive to, and imitative of, caregiver-provided spatial asymmetry.

In sum, by studying the developmental arc of this simple spatial task, one can glean insight into how evolutionary and cultural factors shape human development at a critical time period. The pattern of results documented here solidify the link between space and number (found in infancy, and early childhood) as it spans the key transition point of toddlerhood, and highlights ways in which theorists can use findings from disparate subfields (such as evolutionary psychology, infant psychology, psycholinguistics, and cognitive psychology) to inform our exploration of enculturated development.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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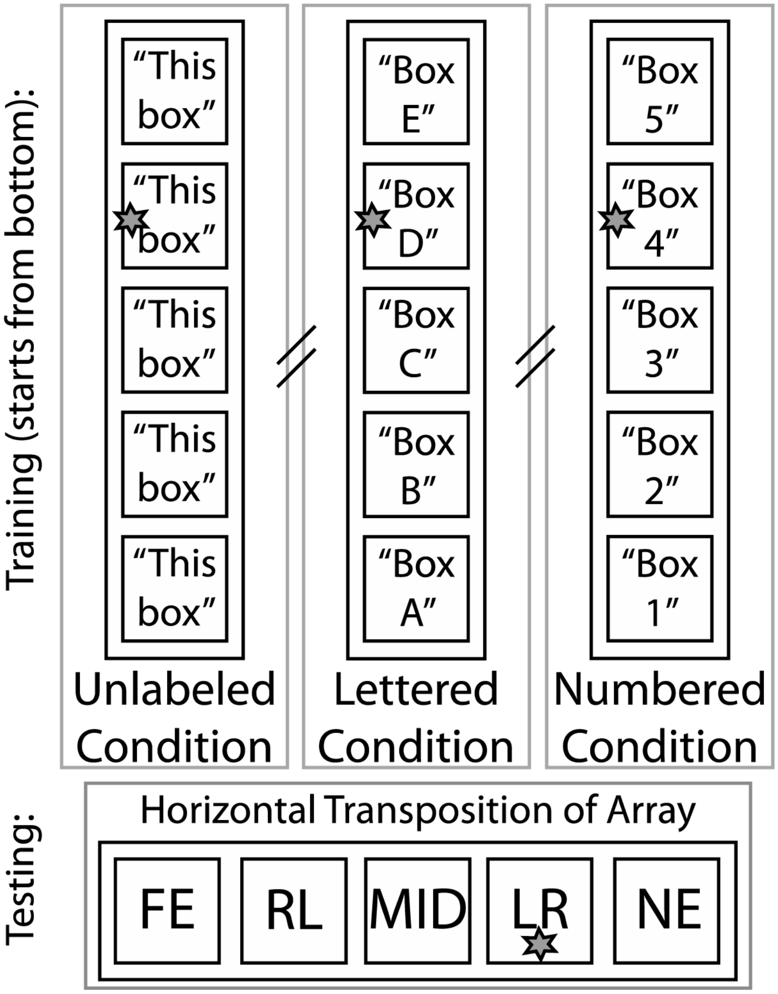

Figure 1.

Schematic of labels used in each condition and position of boxes during training and testing. The star indicates the placement of the hidden object. FE = Far end box, RL = right-to-left mapping box, MID = middle box, LR = left-to-right mapping box, and NE = near end box.

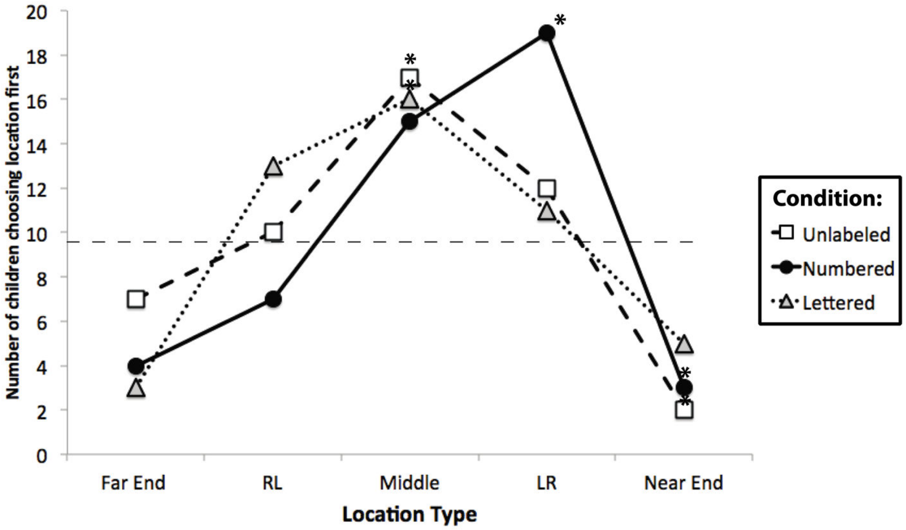

Figure 2.

Toddlers' mapping behavior to a horizontal array, after training on vertical placement. Asterisks indicate significantly different behavior from chance (20%) at an alpha level of .05; the dotted horizontal line indicates chance levels of responding.

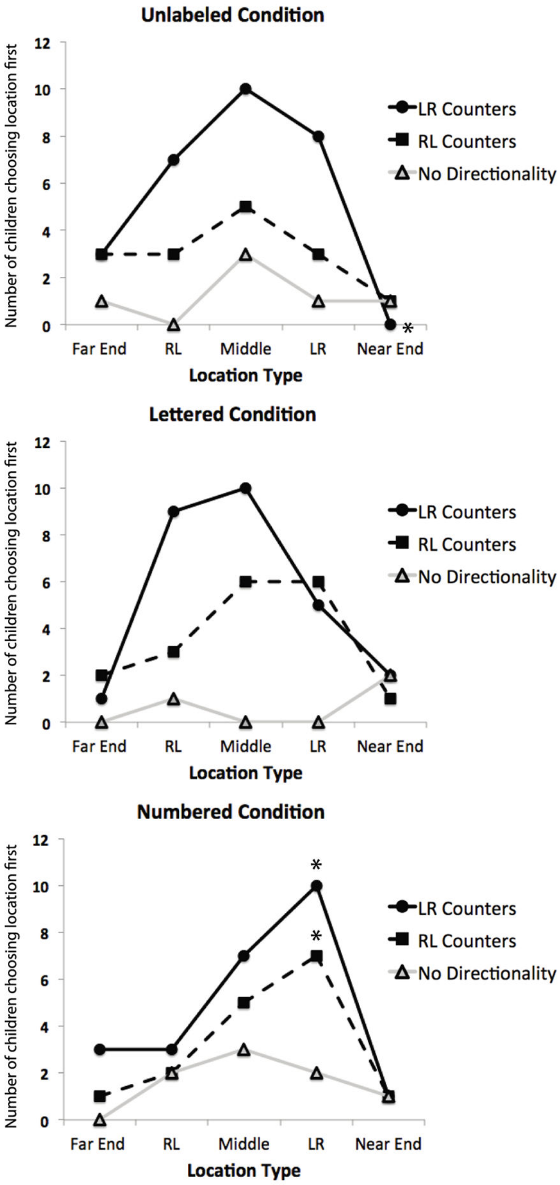

Figure 3.

Toddlers' first choice for each horizontal test location for each condition, plotted as a function of their counting directionality. Asterisks indicate significance above or below chance levels (20%) with an alpha level of .05.