Flexible spatial memory in children: Different reference frames on different axes

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Abstract

Spatial cognition is central to human behavior, but the way we conceptualize space varies over development and across cultures. When remembering the locations or movements of nearby objects, educated adults predominantly rely on a body-based spatial reference frame (e.g. to the left), whereas other groups prefer environment-based frames (e.g. toward the road), at least in some contexts. We propose that this variation in spatial thinking partly reflects differences in the ability to reliably discriminate left-right space, an ability that is common only among educated adults. To evaluate this proposal, here we tested US children's spontaneous use of spatial reference frames on two axes. On the front-back axis, where spatial discrimination was relatively high, participants remembered object locations and movement directions using a body-based reference frame. On the left-right axis, where their spatial discrimination was significantly worse, the same participants preferred environment-based reference frames. This reversal reveals remarkable flexibility in children's spontaneous use of spatial reference frames, extends findings in indigenous adults, and clarifies the likely mechanisms underlying spatial cognitive diversity.

Keywords: Spatial cognition; Frame of reference; Culture; Context; Development

Introduction

Humans are spatial thinkers. Although our extraordinary spatial abilities evolved primarily for navigating and manipulating the physical environment, they also play an essential role in higher-level conceptual development. From early in life, people use space to mentally represent a variety of core conceptual domains, including time (Tillman, Tulagan, Fukuda, & Barner, 2018), emotion (Casasanto & Henetz, 2012), and number (de Hevia, Izard, Coubart, Spelke, & Streri, 2014; McCrink & Opfer, 2014). For example, in many cultures children form a *mental number line*, implicitly associating smaller numbers with the left side of space and larger numbers with the right (Opfer, Thompson, & Furlong, 2010). These spatial-numerical associations facilitate magnitude comparisons, ordinal judgments, and arithmetic operations (Gunderson, Ramirez, Beilock, & Levine, 2012; Thompson & Siegler, 2010) and predict math achievement later in life (Schneider et al., 2018). Beyond the domain of number, spatial reasoning abilities are thought to play a critical role in memory, everyday problem-solving, and success in STEM fields (Gauvain, 1993; Uttal & Cohen, 2012). Conversely, deficits in spatial reasoning have been linked to a variety of other cognitive disorders, including Non-Verbal Learning Disorder (Mammarella, Lucangeli, & Cornoldi, 2010), dyslexia (Vidyasagar & Pammer, 2010), and dyscalculia (Szucs, Devine, Soltesz, Nobes, & Gabriel, 2013). Yet, despite the importance of spatial abilities in people's lives and livelihoods (Tversky, 2005), the mechanisms by which spatial cognition develops are not well understood (Majid, Bowerman, Kita, Haun, & Levinson, 2004).

Clues about the origins of spatial cognition come from studies of its variation. Conceptual structures like the left-to-right mental number line rely on *egocentric* space, a coordinate system defined by the sides of the body (e.g. left, right, front, and back). Although some scholars have argued that body-based spatial *frames of reference* (FoRs) are developmentally primary (Kant, 1768; Piaget & Inhelder, 1948), they are not universally preferred. On the contrary, studies suggest that children have more facility with *allocentric* space, coordinate systems defined by the features of the environment (e.g. walls, hills, and landmarks; e.g. Shusterman & Li, 2016; Nardini, Burgess, Breckenridge, & Atkinson, 2006). For example, when predicting the location of a hidden object, children more easily learned an allocentric spatial rule (e.g. the target object is in the cup nearest to the window) than an egocentric spatial rule (e.g. the target object is in the right-hand cup), as did a sample of non-human primates (Haun, Rapold, Call, Janzen, & Levinson, 2006). This pattern has lead some researchers to conclude that humans may inherit "a preference for allocentric over egocentric spatial strategies" (Haun et al., 2006). However, other studies have found remarkable flexibility in children and infant's FoR use, which varies across testing methods and environments (Li & Abarbanell, 2018; Acredolo & Evans, 1980; Acredolo, 1978). For example, the allocentric advantage children showed in one experiment was eliminated in another experiment by simply changing the relative positions of the testing tables (Li & Abarbanell, 2019). This flexibility supports the claim that "egocentric representations are just as readily available as allocentric representations from the outset" (Li & Abarbanell, 2019), but does not resolve why children favor a given FoR in a given context or why these preferences change over development and vary across groups.

We suggest that this variation in FoR use can be explained in part by differences in spatial perception. Although the physical features of space may be universal, its psychological features vary in surprising ways. For example, research in cognitive linguistics and cognitive neuroscience shows that the left-right (i.e. lateral) axis is peculiar among the egocentric spatial axes. People are notoriously bad at distinguishing left and right, not just in language (e.g. "No, your *other* left"; Cox & Richardson, 1985; Piaget & Inhelder, 1948; Dessalegn & Landau, 2013), but also in visuospatial perception and memory; people fail to distinguish shapes, images, and letters that are left-right mirror images of each other (like "b" and "d") more than they confuse up-down mirror images (like "d" and "q") or other spatial transformations (Bornstein, Gross, & Wolf, 1978; Danziger & Pederson, 1998; Fernandes & Kolinsky, 2013; Cairns & Steward, 1970; Gregory, Landau, & McCloskey, 2011; Dessalegn & Landau, 2008). This *mirror invariance* is evident not only in the brain and behavior of humans (Dehaene et al., 2010; Blackburne et al., 2014; Pegado, Nakamura, Cohen, & Dehaene, 2011), but also of non-human animal species, including macaques (Rollenhagen & Olson, 2000), rats (Lashley, 1938) and octopus (Sutherland, 1960), suggesting it is an evolutionarily ancient feature of visuospatial perception (Corballis, 2018; Dehaene, 2013). The ability to reliably discriminate left-right mirror images develops slowly (in cultures where it is learned), extending into the second decade of life (Blackburne et al., 2014; Xu, Song, & Liu, 2023). This difficulty is also reflected in language: Many language groups lack any terms denoting left and right regions of space (Levinson, 1996; Brown & Levinson, 1992), and in cultures that do have such terms, children are notoriously slow to learn their meanings (i.e. much slower than for terms distinguishing front from back and up from down; Cox & Richardson, 1985; Piaget, 1997). In short, lateral space is tricky, especially for children.

We hypothesized that the difficulty of left-right spatial discrimination influences FoR use (Brown & Levinson, 1993; cf. Li & Abarbanell, 2019). On the *Spatial Discrimination Hypothesis* (Pitt, Carstensen, Boni, Piantadosi, & Gibson, 2022), people tend to encode the spatial properties of objects using the spatial continuum along which they can make better (i.e. more reliable or precise) discriminations, whether that continuum is defined egocentrically or allocentrically. If so, then people who can discriminate egocentric space better on the sagittal axis than the lateral axis (i.e. people with strong mirror invariance) should – as a consequence – use egocentric FoRs more on the sagittal axis than the lateral axis. In other words, when people encode the spatial features of objects in the environment, the relative difficulty of left-right space should lead them to abandon this egocentric axis in favor of more reliable spatial continua, like those defined by salient landmarks.

In line with this proposal, some previous findings have found cross-axis differences in FoR use in indigenous adults (Pederson, 1993; Brown & Levinson, 1993; Shapero, 2017; Marghetis, McComsey, & Cooperrider, 2020), and note the existence of "strong" and "weak" spatial axes in some groups (Brown & Levinson, 1992, 1993; Levinson, 2003). This pattern is exemplified in a study of the Tsimane', an indigenous Amazonian group, in which adults preferentially used egocentric space to remember object arrays along the sagittal axis but used allocentric space when objects were arrayed across the lateral axis (Pitt et al., 2022).

Here, we tested this proposal in another population thought to have strong mirror invariance: US children performed two non-verbal tests of FoR use, a test of mirror invariance, and a test of basic egocentric spatial terms. If FoR use is influenced by differences in spatial discrimination, then even children who know left-right words should show mirror invariance and prefer different FoRs on different axes, as in indigenous adults. By contrast, if non-verbal FoR use is driven by Alternatively, participants could show strong mirror invariance but no cross-axis difference in FoR use, and this result would undermine the Spatial Discrimination Hypothesis and suggest that effects in adult populations were culture-specific.

Methods

Participants

We collected data from 141 English-speaking children (ages 4 - 8 years; mean = 5:9, SD = 1.12) at science museums and parks in the San Francisco Bay Area, and in the Psychology department at UC Berkeley, as part of a larger study. Previous studies suggest that in this age range, children in industrialized cultures struggle with left-right spatial terms and may have more allocentric tendencies than their parents, but can complete spatial memory tasks of the kind we employ (e.g., Shusterman & Li, 2016). Of these, 82 participants completed the Discrimination task, 104 participants completed the Matching task, 59 participants completed the Dance task, and 77 participants completed the spatial language Comprehension tasks. All protocols were approved by the IRB of UC Berkeley. Participants provided verbal assent and guardians provided written consent and neither received compensation.

Discrimination task methods

The Discrimination task served as a test of mirror invariance. Participants performed the task on an Apple iPad, which was laying flat on a table, allowing us to compare discrimination along the lateral and sagittal axes. The experimenter introduced the participant to a cartoon frog named Jumpy, and

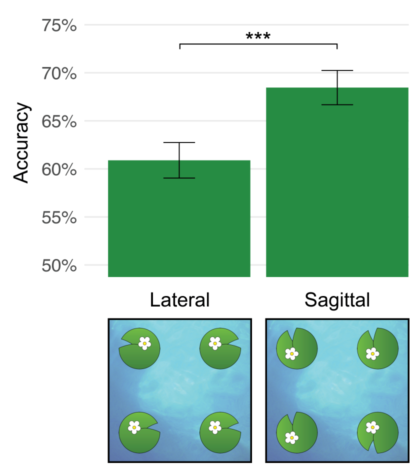

Figure 1: Discrimination task. Participants more accurately identified the odd one of four shapes when it differed by a sagittal flip (right) than when it differed by a lateral flip (left), an index of mirror invariance.

explained that he liked to hide under the lily pad that was different from all the other lily pads, as shown at the bottom of Figure 1. The participant's task was to find where Jumpy was hiding by touching the lily pad that was different from the others, before he swam away. After selecting a lily pad, Jumpy appeared from behind the odd lily pad, providing informative feedback on every trial. Participants began with a series of warm-up trials in a standard order. In four color trials, the odd lily pad was different only in color. In four shape trials, the odd lily pad was different only in shape. In critical trials, the odd lily pad was a mirror image of the others, either across the lateral or sagittal axis. Participants performed four practice trials (with the critical stimuli) and then 16 critical trials (in randomized order), which we composed by crossing the axis of mirror-flipping (lateral or sagittal), the orientation of the standards (rightward or leftward, toward or away), and the position of the oddball (the four corners). Participants were encouraged to respond quickly, but advanced through trials at their own pace.

Matching task methods

The Matching task, adopted from standard tests in "tabletop" space (e.g. Brown & Levinson, 1993), tested which FoR participants used to remember the location of objects. As depicted in Figure 2 (left), participants stood between two square floor mats (a.k.a. "ponds"), one for the experimenter and one for the participant. On each mat was an array of five round ("lily") pads in a "+" formation. In each trial, the experimenter placed a toy on one of the pads on their mat and asked the participant to make their pond "look like" (i.e. match) the experimenter's pond. To do so, the participant retrieved the toy from the experimenter's mat, turned around 180 degrees to face their mat, and placed the toy on one of the pads. A second experimenter recorded the location/orientation of the response, which corresponded to an egocentric match, an allocentric match, or neither.

Participants performed two types of matching trials: Position matching and orientation matching. In position matching trials, the experimenter put a flat plastic sunflower (i.e. with radial symmetry) on each of their five pads. On the first and last of these trials, the experimenter placed the flower on the center pad; These trials have only one correct response and therefore served as comprehension checks. In critical trials, the flower was on the left, right, near, or far pad. In orientation matching trials, which followed position matching trials, the experimenter placed a stuffed animal frog (i.e. a toy with a clear front and back) in the center pad, facing each of four directions – left, right, front, and back. In all, participants performed four critical position matching trials and four critical orientation matching trials in counterbalanced order.

Dance task methods

The Dance task, adapted from Haun and Rapold (2009), tested which FoR participants used to remember a novel sequence of bodily movements (see Figure 2, right). Each trial began with participant and experimenter standing on their respective floor mats, facing in the same direction (i.e. not toward each other) with the participant behind the experimenter, and proceeded through four stages. First, the experimenter demonstrated a short dance, with one primary direction of movement. Second, the experimenter and participant practiced the dance together, still facing the same direction. Third, the experimenter turned around to face the participant, who then practiced the dance alone. Finally, after demonstrating knowledge of the dance, the participant turned around 180 degrees to face a second experimenter and was asked to do the dance again, from memory.

Each participant performed four dances (in a predetermined order that was counterbalanced across participants), which differed only in their primary direction of movement: Right, left, forward, or backward. For example, in the rightward dance, participants took four steps to the right, clapped three times, and then took four steps back to the left, ending up where they had started. In response to participants' dances at test (i.e. recital), the second experimenter provided positive feedback in all cases and recorded the initial direction of movement, which corresponded to egocentric recital, allocentric recital, or neither.

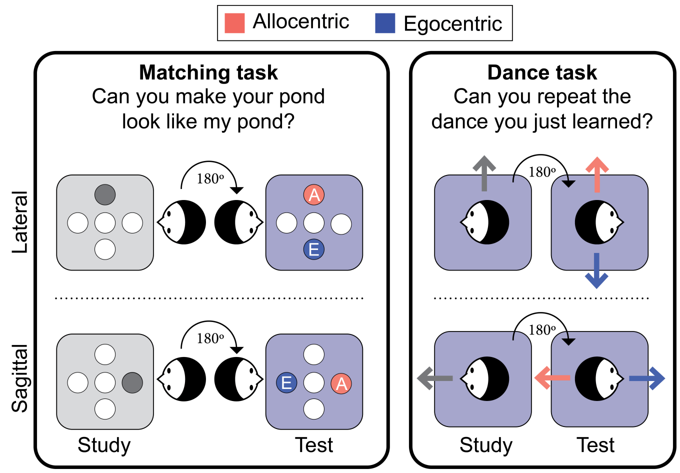

Figure 2: Spatial memory tasks. Participants performed two non-verbal tests of spatial frames of reference, in which they encoded the spatial arrangement of objects (left) or the direction of bodily movements (right) over lateral and sagittal space.

Comprehension tasks

After all other tasks, we tested participant's comprehension of basic sagittal and lateral spatial words in English, in three ways. In the position task, we asked participants to place a toy frog on the pad in *front* of them, *behind* them, to their *left*, and to their *right* (in counterbalanced order). Then, in the orientation task, we asked them to put the frog down facing *away*, *toward*, *left*, and *right* (in counterbalanced order). Finally, in the pointing task, we asked them to point to the *front* and to the *back*, and to raise their *left* and *right* hand, with the order counterbalanced across participants.

Results

Discrimination task results

Participants achieved 97% accuracy in the color task and 93% accuracy in the shape task, demonstrating clear understanding of the task mechanics. Accuracy dropped to 73% in practice trials and to 66% in critical trials, but remained well above chance performance (i.e. 25%). Critically, participants had higher accuracy when comparing sagittal mirror images (71%; $\beta = 1.43, SEM = .22, p < .0001$) than when comparing lateral mirror-images (62%; $\beta = -2.25, SEM = 0.34, p < .0001$), and this cross-axis difference was statistically significant ($\beta = .70, SEM = .19, p = .0002$; see Figure 1), an indication of mirror invariance.

Comprehension tasks results

Overall, participants were significantly above chance in their comprehension of both sagittal and lateral terms ($ps < .001$) but there was a significant difference across axes: Higher accuracy in response to sagittal terms (94%) than lateral terms (76%; $\beta = -4.72, SEM = 1.65, p = .004$), consistent with the results of the non-verbal spatial discrimination task. Although this effect was not significant for any one task, all tasks trended in the same direction, as shown in Figure 3.

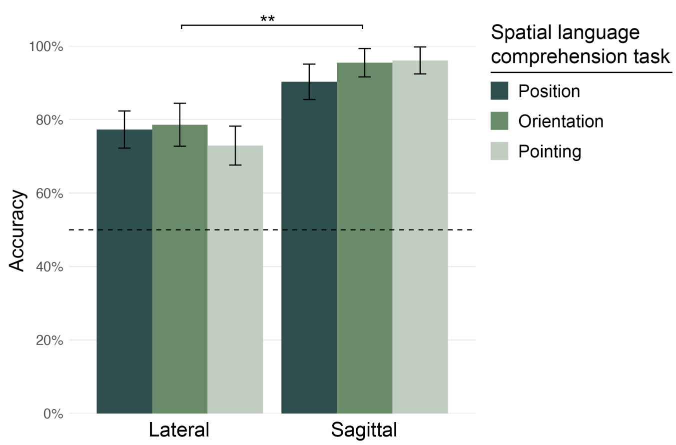

Figure 3: Comprehension tasks results. Participants accurately interpreted egocentric spatial language on both axes, with better performance for front-back words than left-right words.

Matching task results

Participants correctly selected the middle cup 100% of the time, indicating clear understanding of the task. In critical trials, 63% of responses were allocentric, 36% were egocentric, and less than 2% were unclassifiable and were excluded from further analyses. Figure 4 (left) shows the proportions of egocentric vs. allocentric responses on each axis. To analyze these results, we used mixed-effects logistic regression models of individual responses with random subject slopes and intercepts and age as a fixed effect covariate.

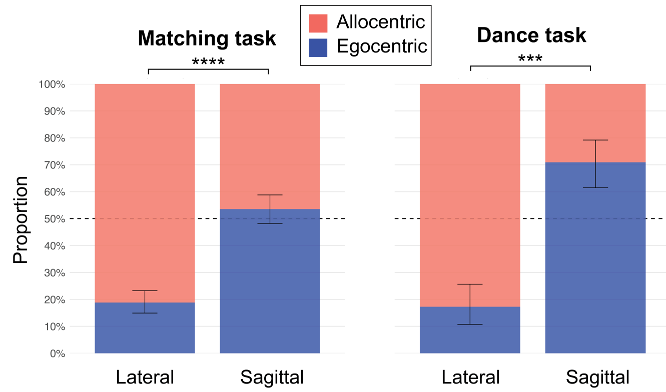

Figure 4: Spatial memory results. In both tasks, participants used different spatial reference frames on different axes. Error bars show binomial, between-subject 95% confidence intervals.

Participants had an overall preference for allocentric space (64% allocentric; $\beta = -2.25, SEM = 0.34, p < .0001$), but this preference differed significantly across spatial axes ($\beta = 2.44, SEM = 0.31, p < .0001$). Participants were overwhelmingly allocentric on the lateral axis (81% allocentric; $\beta = -2.25, SEM = 0.34, p < .0001$) but not on the sagittal axis, where they had a slight but non-significant preference for egocentric responses, (54% egocentric; $\beta = .18, SEM = .18, p = .30$). We found no main effect of age and no interaction between age and axis ($ps > .15$).

Dance task results

Overall, participants' responses in the Dance task were 52% allocentric and 46% egocentric, and less than 2% unclassifiable. Figure 4 (left) shows the proportions of egocentric vs. allocentric responses on each axis, which we analyzed as in the Matching task.

Participants showed a small but significant preference for allocentric responding overall (53% allocentric; $\beta = -6.68, SEM = 2.05, p = .001$), but their response pattern fully reversed across spatial axes ($\beta = 7.63, SEM = 2.04, p = .0002$). Responses were overwhelmingly allocentric on the lateral axis (83% allocentric; $\beta = -6.72, SEM = 2.05, p = .001$) but egocentric on the sagittal axis (71% egocentric; $\beta = 1.00, SEM = .23, p < .0001$). We found no main effect of age and no interaction between age and axis ($ps > .20$).

Discussion

US children used different FoRs on different axes according to a cross-axis difference in spatial discriminability. On the sagittal (i.e. front-back) axis, where spatial discrimination was relatively easy, participants preferred egocentric space when remembering the locations of objects and the directions of bodily movements. On the lateral (i.e. left-right) axis, the same participants showed a different pattern in their spatial memory, with a stronger preference for allocentric space. This pattern replicates and extends findings in indigenous adults, who likewise have shown different patterns of FoR use on different axes in a variety of non-verbal tasks (Pitt et al., 2022; Shapero, 2017; Brown & Levinson, 1993; Marghetis et al., 2020). The generalizability of this pattern shows that it is not specific to adults, to a small set of cultures, or to a small set of experimental tasks. Rather, this cross-axis difference in FoR use may be pronounced in any population in which mirror invariance remains strong, suggesting a common mechanism for developmental change and cultural diversity in FoR use, as posited by the Spatial Discrimination Hypothesis.

Spontaneous spatial flexibility. Previous studies have shown that children have multiple FoRs at their disposal, capable of learning egocentric and allocentric rules (Li & Abarbanell, 2019, 2018; Acredolo, 1978; Acredolo & Evans, 1980) from early in life. However, it has remained unclear which FoR children prefer to use in a given context, and why. Some findings have suggested that children may prefer using allocentric FoRs, even if they are capable of egocentric reasoning. For example, when introduced to novel spatial words with ambiguous meanings (e.g. "This is your *Ziv* side"), US preschoolers tended to interpret them allocentrically, unless experimenters artificially exaggerated egocentric cues (Shusterman & Li, 2016). The present findings suggest that any strong preference for allocentric FoRs may be limited to the lateral axis, where preschoolers are known to struggle with egocentric discrimination. On the sagittal axis, this allocentric preference disappears or reverses, revealing that children spontaneously switch between FoRs from one moment to the next, according to differences in spatial discriminability.

Discrimination, not distance. Although we predicted this cross-axis difference in FoR use on the basis of the Spatial Discrimination Hypothesis, in principle it could reflect differences in participants' use of *distance* information. Specifically, in "tabletop" tasks like our Matching task, participants could use distance to distinguish position on the sagittal axis (i.e. near-far), but not on the lateral axis, since lateral positions did not differ systematically in their distance from the participant (see Figure 2, left). In this case, any cross-axis difference in FoR use could reflect a cross-axis difference in the utility of distance information rather than a cross-axis difference in spatial discrimination (Li & Abarbanell, 2019; Brown & Levinson, 1993; Li & Abarbanell, 2018).

One previous study has found a cross-axis difference in children's FoR use, and attributed it to strategic use of distance information. Shusterman and Li (2016) found that US preschoolers could better learn an egocentric spatial rule for sagittal arrays than lateral arrays of cups when the arrays were located directly in front of the participant, as in our Matching task. To evaluate the role of distance information in this effect, they conducted another experiment in which the table was moved to the side of the participant, with an array that was *parallel* to the participant's sagittal axis, but offset to the left side. This new side-sagittal test eliminated the cross-axis difference, leading the authors to dismiss their previous cross-axis effect and conclude that children "learn to discriminate left vs. right just as well as front vs. back." However, this null effect could reflect the complexity of their side-sagittal task, in which the arrays were sagittal with respect to participants' torso, but lateral with respect to the their heads. This complexity seems to have caused confusion among their participants, whose accuracy dropped precipitously in this version of the task to near 50%.[1]

Our Dance task offers a simpler way to address the role of distance information in FoR use, and yields a different answer. In the Dance task, distance information was no more useful on one axis than on the other, as participants moved the same distance (i.e. 4 steps) in each direction: Right, left, forward, backward. Therefore, if distance information were driving cross-axis differences in FoR use in "tabletop" tasks, then this difference should have disappeared in the Dance task. On the contrary, this difference was even more pronounced: Participants used different FoRs on different axes even when distance was invariant.

Discrimination, not language. Differences in FoR use have often been attributed to differences in language, largely on the basis of cross-cultural correlation: In cultures where egocentric spatial language predominates, people tend to prefer egocentric solutions to spatial memory tasks; In cultures where allocentric spatial language predominates, people generally prefer allocentric solutions (at least when tested on the lateral axis; Majid, 2002; Wassmann & Dasen, 1998; Levinson, 1996; Majid et al., 2004). In principle, a preference for allocentric spatial solutions on the lateral axis (e.g., in young children and indigenous cultures; Shusterman & Li, 2016; Levinson, 1996) could be due to a lack of left-right spatial language.

However, our results suggest language may not play a strong causal role in nonlinguistic FoR use, as participants showed a strong preference for allocentric space on the lateral axis despite generally knowing the words for left and right. To better address the role of egocentric language in our effects, we re-analyzed the Matching and Dance tasks using only the data from participants who scored perfectly on our tests of lateral spatial language. In this subset of participants, the cross-axis effect remained significant in both the Matching task and Dance task ($ps < .01$): Even children who knew with 100% accuracy which side was "left" and which was "right" avoided using left-right space in the spatial memory tasks. This result suggests that the preferences for allocentric space observed in some groups may not be driven by spatial

[1] Moreover, the authors defined chance as 33% but only two of the three cups in the arrays were informative about FoR use, as the correct response for middle cups was the same in either FoR. Therefore, chance is better defined as 50% accuracy, in which case performance (on the only 2 critical cups) was likely indistinguishable from chance. In short, their participants seem to have learned *neither* the egocentric nor allocentric rule in the side-sagittal experiment, making it uninformative about the role of distance in FoR use.

language. Rather, these groups may disprefer lateral spatial language and lateral spatial solutions (in non-verbal tasks) for the same reason: Left-right spatial discrimination is difficult.

Beyond axes: Cognitive diversity at many levels. The Spatial Discriminability Hypothesis predicts differences in FoR use across axes, but this account can also explain variation over development and across cultures. Indeed, egocentric spatial discrimination abilities vary at all of these levels and some evidence suggests that they correlate with FoR use. For example, as people develop in industrialized cultures that emphasize left-right spatial distinctions, their mirror invariance decreases in strength (Danziger & Pederson, 1998; Cox & Richardson, 1985; Ahr, Houdé, & Borst, 2017; Blackburne et al., 2014) and any preference for allocentric space dwindles (at least for small spatial scales; e.g. Haun et al., 2006; Brown & Levinson, 1993). In cultures where left-right spatial distinctions are less important, mirror invariance remains strong throughout adulthood (e.g. Brown & Levinson, 1992; Danziger & Pederson, 1998; Kolinsky et al., 2011) and even adults prefer allocentric FoRs on the lateral axis (e.g. Pitt et al., 2022; Marghetis et al., 2020; Majid et al., 2004; Pederson et al., 1998). Although the evidence to date is purely correlational, we suggest that these developmental and cultural trends may reflect a causal relationship: Children develop into largely egocentric adults if and when cultural practices – like reading, driving, and shaking hands – require them to discriminate left-right space.

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