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Variation in spatial concepts:
Different frames of reference on different axes

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Abstract

The physical properties of space may be universal, but the way people conceptualize space is not. In some groups, people tend to use egocentric space (e.g. left, right) to encode the locations of objects, while in other groups, people encode the same spatial scene using allocentric space (e.g. upriver, downriver). These different spatial *Frames of Reference* (FoRs) characterize the way people *talk* about spatial relations and the way they *think* about them, even when they are not using language. Although spatial language and spatial thinking tend to covary, the root causes of this variation are unclear. Here we propose that this variation in FoR use reflects the *spatial discriminability* of the relevant spatial continua. In an initial test of this proposal in a group of indigenous Bolivians, we compared FoR use across spatial axes that are known to differ in discriminability. In two non-verbal tests, participants spontaneously used different FoRs on different spatial axes: On the lateral axis, where egocentric (left-right) discrimination is difficult, their behavior was predominantly allocentric; on the sagittal axis, where egocentric (front-back) discrimination is relatively easy, their behavior was predominantly egocentric. These findings support the spatial discriminability hypothesis, which may explain variation in spatial concepts not only across axes, but also across groups, between individuals, and over development.

Keywords: Spatial cognition; Frame of reference; Culture; Language; Context; Variation

Introduction

Space is fundamental to human cognition, but people represent space in qualitatively different ways. What is to the "right" of a tree for one person may be "north" to a second person and "upriver" to a third. These different spatial *frames of reference* (FoRs) go deeper than language – they govern the structure of people's spatial concepts even when they are not using language (Majid, Bowerman, Kita, Haun, & Levinson, 2004). This framework for spatial cognition varies between cultures, individuals, contexts, and age groups(Levinson, 1996; Li & Gleitman, 2002; Shusterman & Li, 2016; Haun, Rapold, Call, Janzen, & Levinson, 2006). Yet, despite decades of research, the causes of variation in spatial language and spatial thinking remain unresolved.

Spatial language

By studying the spontaneous (and elicited) use of spatial language across cultures, researchers have identified systematic differences the spatial frames of reference that people use to encode the location and orientation of objects and events in speech (Levinson, 1996; Pederson et al., 1998). Although scholars have proposed various typological systems for precisely classifying spatial language (O'Meara & Báez, 2011; Bohnemeyer & Levinson, 2011), all FoRs can be grouped into two broad categories: egocentric and allocentric. Simply put, egocentric spatial relations depend on the perspective of an observer. For example, when describing the objects shown in Figure 1, an English speaker might say, "The tree is on the left and the man is on the right." The validity of this statement is contingent on the speaker's position and orientation; if she were to move to the opposite side of the table, the man would then be on her left. By contrast, allocentric spatial relations depend only on features of the environment, including global spatial coordinates (e.g. north), geographic features (e.g. the mountains), landmarks (e.g. the church), or the objects themselves (e.g. the man's front). For example, people from Tzeltal (ibid.) or Yupno (Cooperrider, Slotta, & Núñez, 2017) communities might describe the tree in Figure 1 as "uphill" of the man, referencing a salient geographic feature of their environment (rather than a literal incline between man and tree). Critically, the validity of this statement does not depend on the location of the observer(s). Although the speakers of many languages have more than one FoR at their disposal, they often use one FoR preferentially, especially on a given spatial scale (Pederson et al., 1998; Majid et al., 2004; Haun et al., 2006).

Spatial thinking

Spatial reference frames apply not only to the way people *talk* about space, but also to the way they conceptualize it, even when they are not using language. To test which FoRs people use for spatial *thinking* (i.e. nonlinguistic FoRs), researchers have developed behavioral tasks that require spatial memory but not spatial language (Haun et al., 2006; Pederson et al., 1998; Levinson, 1996). For example, in spatial reconstruction tasks (Figure 3), participants learn to reconstruct the position and orientation of a novel array of objects. Having mastered the array at the *study* table, they are then rotated 180 degrees to face the *test* table, and asked to reproduce the same array. Critically, their response depends on the spatial FoR they use to reconstruct the array. If they use egocentric space, their response array will be a 180 degree *rotation* of the original, preserving the position of array objects relative to their perspective (see Figure 3). By contrast, if they use allocentric space, their response array will be a simple *translation* of the original without rotation (except perhaps in contrived circumstances; Li & Gleitman, 2002), preserving its spatial structure with respect to external coordinates (like the room or landscape). In this way, such rotation tasks provide a nonverbal test of the implicit FoRs people use to represent spatial relations.

Determinants of spatial language and thinking

For decades, researchers have debated what factors determine the spatial FoRs people use and why. Some researchers have attributed differences in spatial thinking to differences in spatial language (Levinson, 1996; Majid et al., 2004; but see Li & Gleitman, 2002). Indeed, the FoR that people use in non-verbal spatial reasoning tasks (like the rotation tasks described above) often corresponds to the *linguistic* FoR that is most prevalent in their community (e.g. Pederson et al., 1998). Although language may play a causal role in spatial thinking, it is an unsatisfying explanation for three reasons. First, much of the evidence linking spatial language with spatial thinking is correlational and cross-cultural, and therefore cannot rule out confounding factors (e.g. Pederson et al., 1998). Moreover, evidence from verbal interference suggests that language does not play an online role in determining nonlinguistic FoR use (Carstensen, 2016). Second, the correlation between preferred linguistic and nonlinguistic FoR is far from perfect, leaving substantial cross-cultural variation in spatial thinking unexplained (Pederson et al., 1998; Shusterman & Li, 2016; Majid et al., 2004). Third, FoR use also varies considerably *within* language groups in ways that are difficult to explain on the basis of language alone, between individual adults (e.g. Majid et al., 2004; Shapero, 2017), across contexts (Li & Gleitman, 2002), and over development (e.g. Shusterman & Li, 2016). Even if differences in spatial language could fully account for differences in spatial thinking, this link cannot in principle address the larger question: Why do people differ in the FoR(s) they use *in language or in thought*?

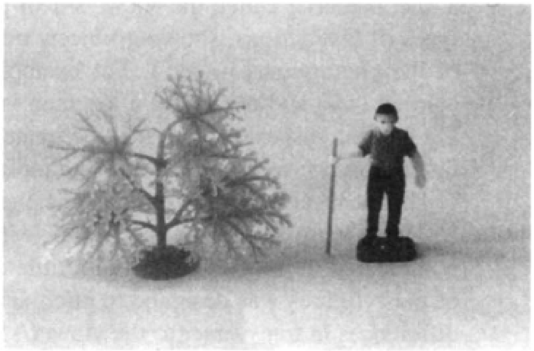

Figure 1: Man and Tree task. Simple spatial arrays are used to elicit language about spatial relations.

According to Li and Gleitman (2002), "the causal engine both for the engrained spatial reasoning styles and the fashions of speech that we find in different communities may well be a derivative of their ambient spatial circumstances." But which circumstances matter and how? Some scholars have suggested that FoR use may ultimately be shaped by the local ecology, the level of urbanization, socio-cultural differences, or other contextual factors (Levinson, 1996; Majid et al., 2004; Mishra, Dasen, & Niraula, 2003; Kagitcibasi, 1997; Shapero, 2017; Li & Gleitman, 2002), but it is unclear whether or how these factors affect FoR use. In short, there is ample evidence of differences in spatial FoRs within and across groups (in both language and behavior), but "no attested mechanism" (Majid et al., 2004) for this variation. As a potential explanation for this variation, we consider people's perception of different spatial continua, using the lateral and sagittal axes as our testbed.

The peculiar nature of left-right space

With some exceptions (Shusterman & Li, 2016; Li & Abarbanell, 2019; Shapero, 2017; Brown & Levinson, 1993; Marghetis, McComsey, & Cooperrider, 2020), researchers have generally relied on the left-right axis in behavioral tests of FoR use, largely ignoring or discounting other egocentric axes (e.g. Pederson et al., 1998; Haun et al., 2006; see Figure 3, top row). Yet, research in cognitive linguistics and cognitive neuroscience shows that the lateral axis is peculiar.

People are notoriously bad at distinguishing left and right, not just in language (e.g. "No, your *other* left!"; Cox & Richardson, 1985; Piaget, 1997[1928]), but also in perception; 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") and other spatial transformations (Blackburne et al., 2014; Danziger & Pederson, 1998; Fernandes & Kolinsky, 2013). On some accounts, this *mirror invariance* may reflect the bilateral symmetry of the brain (Corballis, 2018), deficiencies in interhemispheric coordination (Orton, 1928), or an evolved ability for recognizing objects from a variety of perspectives (Dehaene, 2013; Rollenhagen & Olson, 2000). Alternatively, it could reflect the form of the human body, which is symmetrical across the lateral axis only, and therefore provides no clear way to distinguish the poles of left-right space (Clark, 1973).

The ability to reliably discriminate left-right mirror images, sometimes called *enantiomorphy* (Kolinsky et al., 2011), develops slowly in contexts where it is learned, perhaps continuing into the second decade of life (Blackburne et al., 2014). In contexts without high literacy rates, and where left-right distinctions may have little cultural relevance, enantiomorphy may never develop (Brown & Levinson, 1992;

Kita, Danziger, & Stolz, 2001). This variation of spatial discriminability motivates a new account of FoR use, which we propose here.

The spatial discrimination account of FoR use

Given that non-verbal tests of FoR use have largely been limited to the lateral axis, variation in these tests may reflect differences in the ability to reliably distinguish left-right space, rather than a general FoR preference. Specifically, people who struggle to make left-right spatial distinctions may, as a consequence of this difficulty, abandon this egocentric axis when encoding spatial relations in favor of other spatial continua (e.g. those defined by salient landmarks or geographic features). Consistent with this prediction, some studies have shown different rates of FoR use across axes in other populations (Shusterman & Li, 2016; Li & Abarbanell, 2019; Shapero, 2017; Brown & Levinson, 1993; Marghetis et al., 2020), in both language and behavior.

Based on these observations within and across groups, we propose that a simple principle may govern variation in FoRs across contexts; on this *spatial discriminability* hypothesis, people are more likely to encode the spatial properties of objects using the spatial continuum along which they can make better (i.e. more reliable or precise) distinctions, whether that continuum is defined egocentrically or allocentrically. When the more discriminable spatial continuum is defined by egocentric coordinates (e.g. left-right), people will tend to use an egocentric FoR; when the more discriminable continuum is defined by allocentric coordinates (e.g. uphill-downhill), people will tend to use an allocentric FoR. If so, differences in FoR use within and across groups may be explained by differences in spatial discrimination abilities, as determined by the specifics of one's cultural, linguistic, and bodily experience on multiple timescales (Casasanto, 2016). Consistent with this proposal, previous evidence suggests that left-right spatial discrimination abilities correlate with FoR use across cultures, ages, and individuals (Haun et al., 2006; Shusterman & Li, 2016; Pederson et al., 1998; Brown & Levinson, 1993; Danziger & Pederson, 1998; Ahr, Houdé, & Borst, 2017; Kolinsky & Verhaeghe, 2017).

The present study

As an initial test of this proposal, here we compare FoR use across the lateral (left-right) and sagittal (front-back) spatial axes in the Tsimane', a group of farmer-foragers indigenous to the Bolivian Amazon (Huanca, 2008). Unlike a conventional undergraduate population, Tsimane' adults have little formal education, low levels of literacy, and few of the cultural artifacts that emphasize left-right discrimination in industrialized cultures (e.g. digital interfaces, cars, faucets). Although FoR use has not been previously documented in the Tsimane' language, initial observations suggest a prevalence for allocentric spatial terms (including upriver and downriver). Tsimane' culture may therefore provide an ideal testbed to measure variation in nonlinguistic FoR use across axes, as this would likely be difficult to detect in populations with a strong egocentric bias (like American adults).

Figure 2: A Tsimane' woman studies a lateral array of objects in the reconstruction task, with native Tsimane' translator.

If FoR use in our tasks is governed by the relative discriminability of competing spatial coordinate systems, participants should show stronger egocentric tendencies on the sagittal axis, where near-far egocentric spatial distinctions are relatively easy, than on the lateral axis, where left-right distinctions are more difficult. Alternatively, people could "fixate predominantly on just one frame of reference" (Levinson, 1996; p. 12), in which case the Tsimane's spatial behavior should not differ across spatial axes.

Methods

Participants

Thirty Tsimane' adults, ages 19-64, provided informed consent and participated in two non-verbal tests of their spatial FoRs, and were compensated with goods. All 30 participated in the Selection task and 25 of them also participated in the Reconstruction task. All protocols were approved by the IRB of UC Berkeley.

Design

The two tests of FoR use shared the same basic structure. Two tables were placed parallel to each other in the middle of the room. Throughout testing, the participant stood in between the tables and the experimenter and translator were positioned to their sides (never crossing to the far side of either table). In each trial, participants saw a spatial array – either five identical cups or three different objects – at the study table. In the lateral condition, the array was oriented along the participants' left-right axis; in the sagittal condition, the array was oriented along their front-back axis, and the order of these conditions was counterbalanced across participants. After demonstrating that they had encoded the relevant spatial information at the study table, participants turned around 180 degrees to face the test table, and produced a behavioral response that could be consistent with an egocentric FoR (i.e. the result of rotation), an allocentric FoR (i.e. the result of

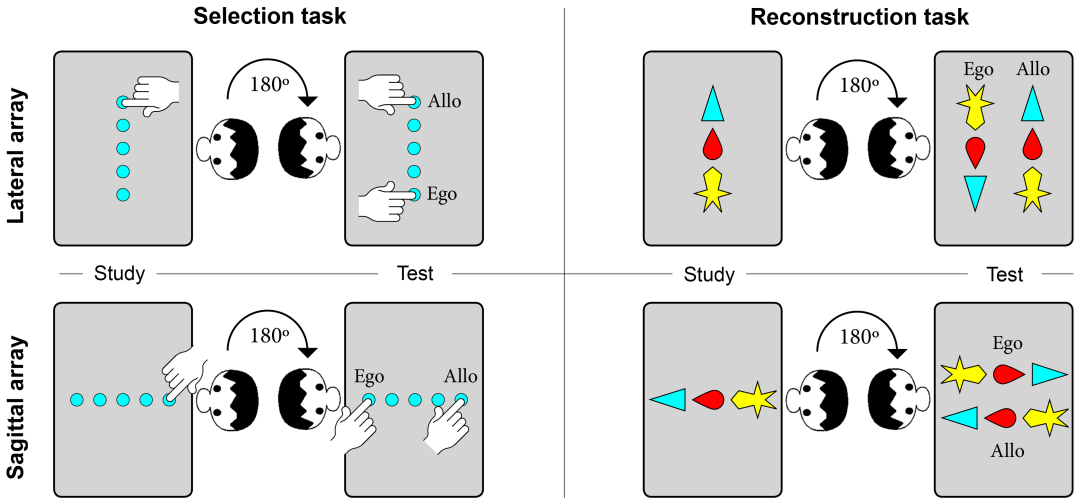

Figure 3: Methods. Participants performed two non-verbal tests of spatial frames of reference, in which they encoded the spatial arrangement of objects arrayed along either the lateral or sagittal axis.

translation), or neither (see Figure 3).[1]

Selection task

In the Selection task (Figure 3, left), adapted from the "chips task" described in Levinson, participants viewed five identical plastic cups on the study table, arrayed either laterally or sagittally. In each trial, the experimenter touched one of the cups in the study array and asked the participant to do the same, to ensure they had encoded which was the target cup. The participant then turned around 180 degrees to face the test table, where five additional cups were also arrayed in the same orientation, and was asked to touch the cup that was in the "same" position as in the test array. The experimenter followed a standard sequence for each participant, touching each cup without speaking (lateral sequence: middle, left, right, mid-left, mid-right, middle; sagittal sequence: middle, near, far, mid-near, mid-far, middle). As the middle cup had a single correct answer regardless of FoR, these trials served as a comprehension check. Note that each test array therefore yielded four critical responses.

Reconstruction task

The reconstruction task (Figure 3, right) was based on the "animals-in-a-row" task used by Pederson et al. (1998), but rather than animals we used other objects with asymmetric fronts and backs (e.g. a pen, coffee scoop, spoon). Each axis was tested twice using two sets of three objects and the order of sets and axes was crossed and counterbalanced across participants. In each trial, participants were presented with a (lateral or sagittal) array of three objects at the study table, where they practiced reconstructing the array (Figure 2). Any errors during these practice trials were pointed out by the experimenter. After having correctly reconstructed the array twice at the study table (i.e. correct position and orientation along primary axis), participants turned around 180 degrees to face the test table and were asked to reconstruct the array again there. The experimenter recorded the position and orientation of each object in the response arrays.

Results

Selection task

Participants correctly identified the middle cup 92.5% of the time (95% in trial 1 and 90% in trial 6), indicating clear understanding of the task. Overall, 50.0% of responses were allocentric, 45.8% were allocentric, and only 3.8% did not correspond to either. The rate of these other responses did not differ significantly across axes (i.e. lateral: 5 responses; sagittal: 4 responses). Figure 4 (left) shows the proportions of egocentric vs. allocentric responses on each axis, with bootstrapped, within-subject 95% confidence intervals. To analyze these results, we used mixed-effects logistic regression models of individual responses with random subject slopes and intercepts and fixed effects of schooling, age, and axis order (e.g. lateral then sagittal) as covariates.

As evident in Figure 4, participants' responses were reliably allocentric on the lateral axis (70.3% allocentric; $\beta = -1.99, SEM = 0.69, p = .004$) but this pattern reversed on the sagittal axis, where participants had a reliable preference for egocentric responses, (75.0% egocentric; $\beta = 2.58, SEM = 0.70, p = .0002$). Critically, participants' FoR use differed significantly across axes ($\beta = 4.75, SEM = 0.93, p < .0001$), an effect with interacted with education; participants with more years of formal schooling showed a marginally weaker effect of axis ($\beta = -1.75, SEM = 0.90, p = .053$), perhaps because reading experience increases use of left-right space. This reversal of FoR use at the group level was also found in the majority of individual participants, two-thirds of whom

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[1] Although other versions of these tasks are capable of distinguishing between subclasses of allocentric FoRs (i.e. intrinsic v. absolute; Levinson, Kita, Haun, & Rasch, 2002), our tasks are designed only to distinguish between egocentric and allocentric FoRs.

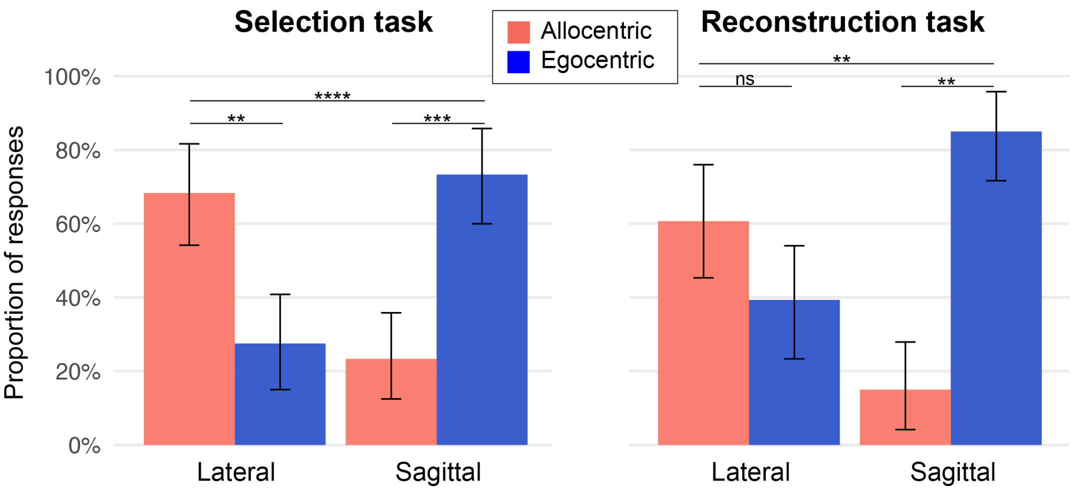

Figure 4: Results. In both tasks, participants preferentially responded allocentrically on the lateral axis and egocentrically on the sagittal axis. Error bars show bootstrapped, between-subject 95% confidence intervals.

responded more allocentrically on the lateral axis and more egocentrically on the sagittal axis.

Reconstruction task

The position and orientation of objects in participants response arrays was 35.5% egocentric, 55.7% allocentric, and 9.0% neither. The rate of these other responses did not differ significantly across axes (i.e. lateral: 9 objects; sagittal: 18 objects; $\chi^2 = 2.60; p = 0.11$). Figure 4 (right) shows the proportions of egocentric vs. allocentric responses on each axis, with bootstrapped, between-subject 95% confidence intervals. Using the same analysis models, we found the same qualitative pattern of results as in the Selection task: FoR use differed reliably across axes ($\beta = 9.79, SEM = 3.32, p = .003$). On the lateral axis, participants showed a slight preference for allocentric responses, but this preference did not differ reliably from chance (60.0% allocentric; $\beta = -1.99, SEM = 1.06, p = .19$). Again, they showed the opposite pattern on the sagittal axis, with a reliable preference for egocentric responses (84.9% egocentric; $\beta = 2.58, SEM = 3.11, p = .002$). This group-level pattern was again found in the majority of individual participants, 62.5% of whom responded more allocentrically on the lateral axis and more egocentrically on the sagittal axis.

Discussion

In two tests of spatial thinking, Tsimane' adults used different FoRs on different spatial axes to represent spatial relations among objects; participants preferentially used allocentric space on the lateral axis and egocentric space on the sagittal axis. These findings show that nonlinguistic FoR use varies not only within and across groups, but also across axes, even *within* individuals. This provides a cautionary note on the classification of language groups according to what appears to be their "predominant" FoR (Levinson, 1996). Rather, we show that the FoR that is predominant on the lateral axis can be dispreferred on the sagittal axis. As these findings suggest, this variation in FoR use may be determined (at least in part) by the spatial discriminability of the relevant spatial continua; where egocentric spatial discrimination tends to be difficult (i.e. on the lateral axis), participants preferred allocentric space; where egocentric spatial discrimination is relatively easy (i.e. on the sagittal axis), the same participants preferred egocentric space.

In principle, the difference we observed across axes could reflect differences in participants' use of *distance* to represent spatial relations. Specifically, participants could have encoded the lateral arrays according to their (allocentric) *positions* (e.g. upriver-downriver) but encoded the sagittal arrays solely based on *distance* from some landmark (i.e. near-far). If they used their own body as such a landmark (i.e. distance from me), then participants could produce more egocentric-consistent responses on the sagittal axis than on the lateral axis, as we observed, without encoding spatial position at all (Li & Abarbanell, 2019; Brown & Levinson, 1993). However, this possibility is inconsistent with three aspects of the data. First, in the reconstruction task, participants used egocentric space on the sagittal axis to encode not only the locations of objects but also their orientations (e.g., facing me), a spatial feature for which distance is not sufficient. Second, participants show no accuracy advantage on the sagittal axis. If distance information were useful for encoding sagittal arrays, then participants' performance should be better on that axis, yet we found a small trend in the opposite direction: Participants produced numerically (but not significantly) more untypable "other" responses on the sagittal axis than on the lateral axis overall. Finally, if participants used distance to encode sagittal arrays, this strategy might be expected to carry over to the lateral arrays that followed, increasing participants' use of allocentric spatial cues (i.e. landmarks) on those trials. Yet, there was no sign of such an order effect in either task (*ps* > .60); the effect of axis on participants' responses was the same regardless of which axis was tested first. Therefore, the difference we observed across axes likely reflects not just a difference in heuristic strategy, but in FoR.

These findings complement findings in other populations, where FoR use has also been observed to differ across axes (Shusterman & Li, 2016; Li & Abarbanell, 2019; Shapero, 2017; Brown & Levinson, 1993; Marghetis et al., 2020). In one study of co-speech gestures, FoR use varied across axes among adults with basic knowledge of left-right words (and not with broader cross-linguistic differences; Marghetis et al., 2020), consistent with our findings. Other cross-axis differences in FoR use have been found in people who have mastered egocentric spatial terms for sagittal distinctions (i.e. front-back) but not for lateral distinctions (i.e. left-right), including young children (Shusterman & Li, 2016; Li & Abarbanell, 2019) and indigenous adults (Shapero, 2017; Brown & Levinson, 1993). Therefore, the cross-axis differences observed in those groups could reflect a cross-axis difference in spatial language or spatial discrimination (or both). Here, nearly all of our participants could correctly label their left and right sides (as measured in a separate task), suggesting that the observed effect was not due to a shortage of egocentric spatial language. Moreover, no previous study has found a *reversal* of FoR use across axes. Rather, the observed patterns of nonlinguistic FoR use have been consistent with the predominant FoR in their respective language communities on both axes, just to different extents. By contrast, here we show *opposite* patterns of FoR use depending on the spatial axis; what the Tsimane' preferred on one axis, they dispreferred on the other. This reversal cannot easily be aligned with the claim that spatial relational thinking is predominated by a single FoR, whether that FoR is given by language (Majid et al., 2004) or by default (Kant, 1991).

Is this cross-axis pattern of nonlinguistic FoR use reflected in language? To our knowledge, previous studies have not systematically compared linguistic FoR use across spatial axes, but doing so has the potential to clarify the role of language in non-linguistic FoRs. Specifically, if linguistic and nonlinguistic FoR use were to show different patterns across axes, then language could not account for the observed difference across axes. Alternatively, linguistic and non-linguistic FoRs could pattern together across axes, but such a correlation would not clarify the causal relationship between them, which could reflect a common cause that shapes them both. We suggest that this common cause may be the spatial discriminability of the relevant spatial continua, but further research is needed to test this proposal.

Here we showed that the spatial discriminability hypothesis predicts the pattern of FoR use across axes, but this account also has the potential to explain variation in FoR use over development, between individuals, and across cultures. Indeed, spatial discrimination abilities vary at all of these levels (Kolinsky & Verhaeghe, 2017; Cox & Richardson, 1985; Danziger & Pederson, 1998) and some evidence suggests that they correlate with FoR use. For example, whereas adults from industrialized cultures are practiced in left-right discrimination and tend to prefer egocentric space, adults in some unindustrialized groups show relatively low left-right discrimination abilities (Danziger & Pederson, 1998) and tend to prefer allocentric FoRs on the lateral axis (Pederson et al., 1998). A similar correlation is observed across age groups; children show poor left-right discrimination abilities (Cox & Richardson, 1985; Ahr et al., 2017) and tend to use allocentric FoRs on tests of the lateral axis, even in cultures where adults prefer egocentric FoRs (Shusterman & Li, 2016; Li & Abarbanell, 2019; cf. Haun et al., 2006). The gradual development of spatial discrimination abilities (i.e. overcoming mirror invariance) can explain not only children's egocentric shift in FoR use (as observed in some cultures), but also their acquisition of left-right words, which they master years after words for up-down and front-back (Cox & Richardson, 1985; Piaget, 1997[1928]). In this way, spatial discrimination abilities may account for developmental changes in both spatial language and spatial thinking.

If the spatial discrimination hypothesis is correct, understanding FoR use will depend on clarifying which experiences influence spatial discriminability, and how. For example, reading and writing in English entails overcoming mirror invariance, training learners to distinguish mirror-image characters (like "b" and "d"; Cox & Richardson, 1985). In languages like Tamil, which have no such mirror-image characters, the left-right discrimination abilities of literate adults were found to be little better than those of illiterate adults (Danziger & Pederson, 1998; Pederson, 2003), suggesting that this ability is shaped by the spatial features of reading and writing, rather than by education more generally. Beyond reading and writing, other cultural practices predict differences in spatial discrimination abilities. For example, among illiterate adults in Portugal, left-right discrimination was significantly better among those who practiced lacemaking, which involves making mirror images of the same pattern, than those who did not (Kolinsky & Verhaeghe, 2017). On the spatial discrimination hypothesis, *any* experience that encourages a person to distinguish the poles of a given spatial continuum (e.g. left-right, uphill-downhill) should make that person more likely to use that continuum to represent spatial relations. In this way, FoR use may be shaped by a wide variety of spatial experiences, as they vary between groups, across contexts, among individuals, and over time.

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