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Multidimensional spatial memory: One action, two reference frames

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Multidimensional spatial memory: One action, two reference frames

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Abstract

Spatial cognition is fundamental to human behavior, but people differ in how they remember spatial relations, variably using body-based (*egocentric*) and environment-based (*allocentric*) spatial reference frames. Despite decades of study, the causes of this variation and flexibility in spatial memory remain unclear. Here we show that people spontaneously use different reference frames on different spatial axes at the same time. When remembering the placement of a target object in a 2-dimensional array, Indigenous Tsimane' adults preferentially used allocentric space to determine lateral placement and egocentric space to determine sagittal placement in the same action. This effect of axis was also significant among US university students, whose overall preference for egocentric space was stronger on the sagittal than lateral axis. These findings support a novel account of spatial cognitive diversity and suggest that people across cultures habitually integrate egocentric and allocentric spatial reference frames into the same action.

Keywords: Spatial cognition; Frame of reference; Culture; Context; non-WEIRD

Introduction

Humans have extraordinary spatial abilities that allow us to navigate across vast forests, mountain ranges, and oceans (Davis & Cashdan, 2019; Fernandez-Velasco & Spiers, 2023), perform complex bodily actions from knitting to karate, distinguish tiny differences in size and shape (Yau, Kim, Thakur, & Bensmaia, 2016), and remember the spatial structure of our surroundings in exquisite detail, even without vision (Tversky, 2019; Teng, Puri, & Whitney, 2012). Spatial representations also support high-level cognition in a variety of domains, including memory, problem-solving, and abstract reasoning (Gauvain, 1993; Uttal & Cohen, 2012; Gunderson, Ramirez, Beilock, & Levine, 2012; Casasanto, 2010). Despite playing a fundamental role in human behavior, mental representations of space vary dramatically within and across groups.

Even the simplest spatial relationships can be characterized in multiple ways. For example, in the phrase "The fork is right of the plate, pointing away," the fork's position and orientation are defined by the sides of the observer (i.e. her *right* and her *front*). This use of *egocentric* (i.e. body-based) space is standard among literate adults, but is less common among many other groups, including adults from unindustrialized cultures (Levinson, 1996; Majid, Bowerman, Kita, Haun, & Levinson, 2004). Rather, such groups often prefer *allocentric* space, a coordinate system defined by the features of the environment, as in "The fork is north of the plate, facing the window." Importantly, these different spatial *frames of reference* (FoR) characterize not only the way people habitually describe spatial relations in language, but also the way they habitually *conceptualize* those relations, as revealed by a variety of elegant behavioral tasks. For example, when asked to reconstruct an array of objects in a new location from memory, some people preserve the egocentric spatial relations of the original array (e.g. maintaining objects' left-right positions), whereas others violate them in order to preserve the allocentric relations (e.g. window side – door side; Pederson et al., 1998). In other tasks, this distinction between egocentric and allocentric space also determines the way people learn new dance routines (Haun & Rapold, 2009; Pitt, Aalaei, & Gopnik, 2023), remember the location of hidden objects (Haun, Rapold, Call, Janzen, & Levinson, 2006), track pathways through a maze (Brown & Levinson, 1993), and gesture about spatial events (Marghetis, McComsey, & Cooperrider, 2020; Kita, Danziger, & Stolz, 2001). Decades of studies in children and adults across a wide variety of cultures reveal remarkable diversity in FoRs use (e.g. Acredolo, 1978; Pederson et al., 1998; Haun et al., 2006; Levinson, 1996; Wassmann & Dasen, 1998; Shusterman & Li, 2016), but the causes of this spatial cognitive diversity remain largely unresolved (Majid et al., 2004).

On one account, differences in FoR use may be caused in part by differences in people's ability to make spatial discriminations (Brown & Levinson, 1993; Li & Gleitman, 2002; Li & Abarbanell, 2019; Pitt, Carstensen, Boni, Piantadosi, & Gibson, 2022). Some spatial continua – notably the left-right continuum – are more difficult to discriminate than others, leading many human groups and non-human animals to conflate shapes with their left-right mirror images more than with their up-down mirror images or other spatial transformations (Bornstein, Gross, & Wolf, 1978; Fernandes, Leite, & Kolinsky, 2016; Gregory, Landau, & McCloskey, 2011; Dehaene et al., 2010; Blackburne et al., 2014; Pegado, Nakamura, Cohen, & Dehaene, 2011; Rollenhagen & Olson, 2000; Sutherland, 1960). For example, children in high-literacy cultures spend years learning to distinguish the letters "b" and "d", even after they have learned to distinguish "b" and "p" (Cairns & Steward, 1970; Rudel & Teuber, 1963; but see Nardini, Atkinson, & Burgess, 2008). Likewise, adults in many unindustrialized cultures often conflate characters, shapes, and objects with their left-right reflections, even when viewing both mirror-images simultaneously (Danziger & Pederson, 1998; Danziger, 2011; Pederson, 2003; Brown & Levinson, 1992). Decades of research show that this *mirror invariance* is the default in the animal world and that reliably distinguishing left-right spatial orientation is a cognitive skill found primarily among literate adult humans (but see Kolinsky & Verhaeghe, 2017). We suggest that doing so helps to explain their reliance on left-right space – an egocentric spatial continuum

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– when encoding spatial relations among nearby objects, as typically observed in studies of educated adults. Conversely, those with little formal education, who do not reliably discriminate left-right space, may often abandon that egocentric continuum in favor of continua they can better discriminate, namely those defined by the environment (i.e. allocentric FoRs; e.g. Pederson et al., 1998; Majid et al., 2004). More generally, according to our *Spatial Discrimination Hypothesis*, in order to remember the spatial relations among objects, people tend to use whichever spatial continuum they can better discriminate in a given context, whether that continuum is defined egocentrically or allocentrically (Pitt et al., 2022).

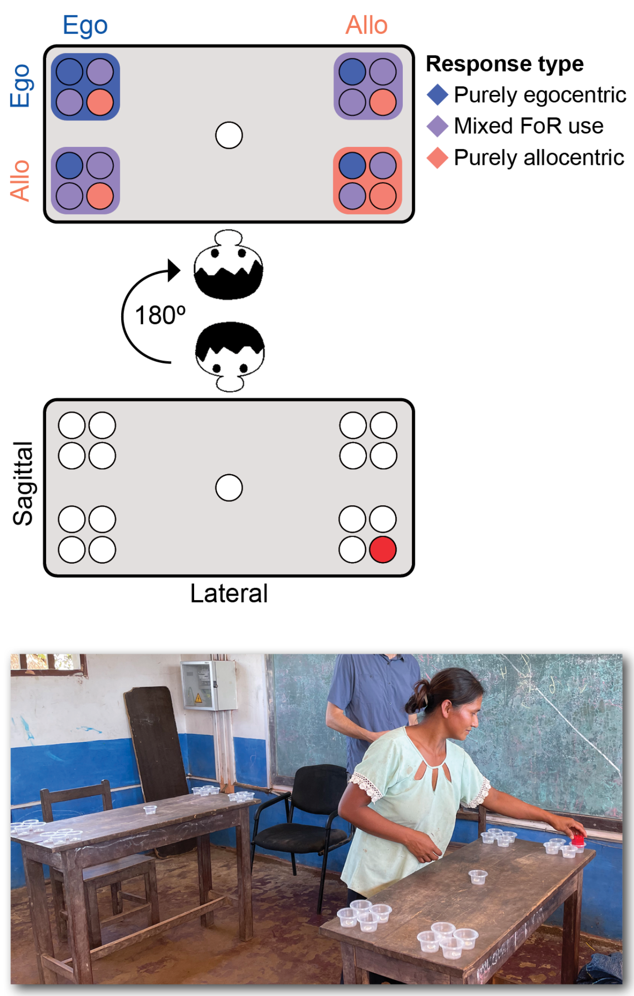

Figure 1: The 4Quads task. Participants viewed an object in one of 16 cups at the study table and were asked to place it in the same cup on the test table, after turning 180°. Top: We classified the reference frame of each response on each axis (i.e. lateral and sagittal) at the quads level (rounded squares) and at the cups level (circles). Bottom: A Tsimane' woman performing the 4Quads task.

Initial support for this hypothesis comes from studies of children and indigenous adults, including the Tsimane', an indigenous farmer-forager group living in the Bolivian Amazon (Pitt et al., 2022, 2023). Participants viewed linear arrays of objects that were aligned either with their lateral (i.e. left-right) or sagittal (i.e. front-back) axis. When asked to describe, match, or reconstruct these arrays from memory, they preferred using allocentric space on the lateral axis, where egocentric discrimination is often difficult, but preferred egocentric space on the sagittal axis, where egocentric discrimination is relatively easy (also see Pederson, 1993; Brown & Levinson, 1993; Shusterman & Li, 2016; Shapero, 2017; Li & Abarbanell, 2019; Marghetis et al., 2020). Although these results show remarkable flexibility, their generalizability remains uncertain. In these studies, the relevant spatial axis varied between trials: Some trials tested the lateral axis, others tested the sagittal axis. However, spatial scenes rarely vary on only one axis at a time, outside such experimental contexts. Rather, in more naturalistic settings – like planting a field, building a shelter, or setting a dinner table – people must reason about multidimensional (i.e. 2D and 3D) spatial relations among many objects.

Here, we asked whether people faced with such complex spatial settings would spontaneously use different FoRs on different axes at the same time, in the same action. In a novel test of spatial memory – the 4Quads task – Tsimane' and US adults saw an object placed in one of 16 critical cups (arranged in four groups of four; see Figure 1), turned around 180° to face an identical 2D-array of cups, and were asked to place the object in the corresponding cup. Critically, this spatial matching task required participants to respond on both the lateral and sagittal axis at once (since cups varied in both their lateral position and sagittal position on the table). This layout allowed us to test which FoR they used on each axis in each action (i.e. cup choice). The Spatial Discrimination Hypothesis predicts differences in FoR use across axes and across cultures. Specifically, if participants can use multiple reference frames simultaneously, then Tsimane' participants should more strongly prefer egocentric FoRs on the sagittal axis than on the lateral axis *in the same action*, as they did for different actions (Pitt et al., 2022). This difference should be smaller (or non-existent) among US adults, a population that is relatively experienced in making left-right spatial discriminations. Alternatively, integrating multiple reference frames into the same action could be unintuitive or cognitively taxing for any population, leading participants to use a single FoR in each individual action, even among those who would prefer different FoRs on different axes when tested separately.

Methods

Participants

Forty-two Tsimane' adults participated in exchange for household goods in the local community schoolhouses in Bolivia. Task instructions were translated by professional Spanish-Tsimane' bilinguals. Sixty-eight US adults participated in exchange for university course credit in the Psychology department at the University of California, Berkeley. We established a target range for our samples sizes a priori, and the final samples were determined by the duration of our fieldwork in Bolivia (for Tsimane' participants) and the duration of the academic term at UC Berkeley (for our US participants). Consenting, testing, and recording protocols were approved by the Institutional Review Board at UC Berkeley.

Procedure

In the 4Quads task, participants stood facing the study table, where they saw an array of 17 identical plastic cups: Four sets of four cups (i.e. 4 quads) in each corner of the table plus one cup in the center (see Figure 1). Participants were told the task was designed to test their spatial memory. In each trial, the experimenter placed an object into the target cup on the study table and asked the participant to pick up the object, turn around 180° to face the test table, which had an identical array of 17 cups, and place it in the cup that was in the "same" position (i.e. the corresponding cup in the corresponding quad). In the first trial, the target was the center cup, which has a single correct answer. After successfully completing this practice trial, participants performed 16 critical trials (i.e. one in each of the 16 critical cups) in one of two pre-determined orders. The experimenter stood beside or behind the participant, facing the same direction (i.e. shared perspective) at study and at test. Participants' geocentric heading at test was varied across testing sessions (even in the same testing room) in order to counterbalance any incidental alignment of salient landmarks (e.g. walls, windows, furniture) with the spatial axes of interest.

Response coding

Each response preserved the object's egocentric or allocentric position on each axis, at each of two levels. To analyze responses at the quads level, we classified the position of the chosen quad on the table while ignoring which of the four cups participants' chose within the quad (see rounded squares in Figure 1). To analyze responses at the cups level, we classified the position of the chosen cup in its quad while ignoring the position of the quad on the table (see colored circles in Figure 1). Therefore, each response corresponded to four data points (i.e. 2 axes $\times$ 2 levels).

Results

To test FoR use across axes for each group, we used a generalized mixed-effects regression in R (R Core Team, 2023), in which FoR was predicted by axis, level, and their interaction, with random subject slopes and intercepts by level. Logistic models were fit using the *lme4* package (Bates, Mächler, Bolker, & Walker, 2015) and inferential statistics were computed using *emmeans*.

Tsimane' responses

Overall, Tsimane' participants showed a slight but significant preference for allocentric responding (52%; $\beta = -.61, SEM = .15, p < .001$). However, their responses differed categorically across spatial axes ($\beta = -2.46, SEM = .36, p < .0001$; see Figure 2, left), consistent with previous findings in this culture: They preferred allocentric responding on the lateral axis ($\beta = -1.55, SEM = .31, p < .0001$) and egocentric responding on the sagittal axis ($\beta = 0.91, SEM = .18, p < .0001$). We found the same pattern of results on both the quads level and cups level, but the effect of axis was larger on the quads level ($\beta = 2.66, SEM = .52, p < .0001$).

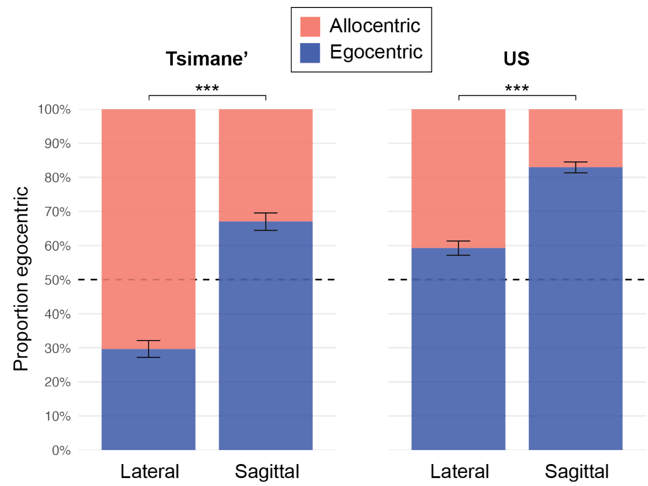

Figure 2: FoR use on each axis. Dashed line shows chance and error bars show binomial 95% confidence intervals.

Unlike in previous studies, here participants chose both lateral and sagittal position at once, allowing us to analyze which FoR participants used on each axis *in each individual response*. As shown in Figure 3, Tsimane' adults gave purely egocentric responses (19%) – that is, responses that were egocentric on both the lateral and sagittal axes – and purely allocentric responses (22%) in roughly equal proportions, but most of their responses (59%) were mixed, reflecting different FoRs on different axes. Specifically, the most common response in this group – accounting for nearly half (48%) of all responses – was allocentric on the lateral axis and egocentric on the sagittal axis. For example, on this pattern, participants who retrieved the object from the far left cup at the study table would place it in the far *right* cup at the test table (see Figure 1). The opposite pattern was the least common response: Only 11% of Tsimane' responses maintained egocentric position on the lateral axis and allocentric position on the sagittal axis. The proportions of these mixed responses differed significantly from chance at both the quads and cups level, according to exact binomial tests (*ps* $< .0001$).

In contrast to Tsimane' adults, US adults showed a clear preference for egocentric FoRs on both the lateral axis (59% egocentric; $\beta = 2.84, SEM = 1.13, p = .01$) and sagittal axis (83% egocentric; $\beta = 7.46, SEM = 1.23, p < .0001$; see Figure 2), consistent with previous findings in educated adults. However, this egocentric preference was significantly stronger on the sagittal axis than on the lateral axis ($\beta = -4.62, SEM = 1.24, p = .0002$), an effect that obtained at both the quads level and cups level (*ps* $< .01$). This cross-axis difference largely reflects participants' frequent use of mixed-FoR responses, as shown in Figure 3. Although the most common response in this group was purely egocentric (58%), the second most common – accounting for one of every four responses – was the same response that predominated among Tsimane' (i.e. egocentric on the sagittal axis and allocentric on the lateral axis) and the opposite pattern was again the least frequent (1%). As among Tsimane', the proportions of these mixed responses differed significantly from chance at both the quads and cups level, according to exact binomial tests (*ps* < .0001).

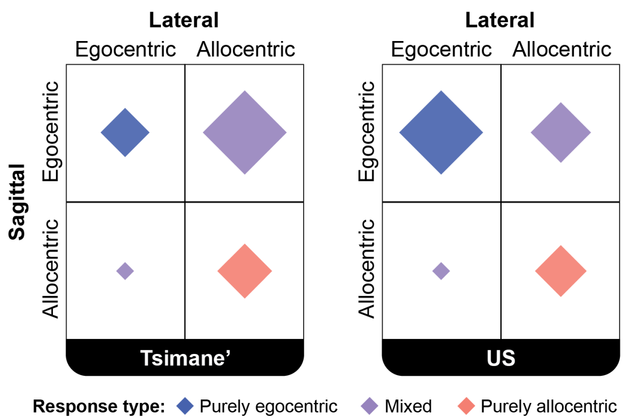

Figure 3: Multidemensional response types. The size of the diamonds is proportional to the total number of responses of each type (pooling quads- and cups-level responses).

Discussion

The way people conceptualize space varies not only between groups and over development, but also across spatial axes in the same individual and even in the same action. In a novel test of multidimensional spatial memory, indigenous Tsimane' adults preferentially used allocentric space to specify lateral position but used egocentric space for sagittal position at the same time. US adults showed a significant cross-axis difference in the same direction, preferring egocentric space more strongly on the sagittal axis than lateral axis, as predicted by the Spatial Discrimination Hypothesis. These findings show that people across cultures – even those with overwhelmingly egocentric tendencies – spontaneously use multiple spatial reference frames when encoding the spatial relations among objects, with important implications for theories of spatial cognition.

Multidimensional spatial memory

Although some studies have tested FoR use on multiple axes (Pederson, 1993; Brown & Levinson, 1993; Shusterman & Li, 2016; Shapero, 2017; Li & Abarbanell, 2019; Marghetis et al., 2020; Pitt et al., 2022, 2023), or noted the existence of "strong" and "weak" spatial axes in some groups (Brown & Levinson, 1992, 1993; Levinson, 2003), the large majority of studies on this topic have focused on the lateral axis alone (e.g. Pederson et al., 1998; Haun et al., 2006; Levinson, 1996; Haun & Rapold, 2009). This unidimensional selection bias has lead some researchers to suggest that cultures "fixate predominantly on just one frame of reference" (levinson1996frames; also see wassmann1998balinese), even if they have access to many: Some groups are generally egocentric, others are generally allocentric (e.g., Levinson, 1996; Levinson, Kita, Haun, & Rasch, 2002; Majid et al., 2004; Bohnemeyer & Levinson, 2011; Haun, Rapold, Janzen, & Levinson, 2011; Haun et al., 2006; Wassmann & Dasen, 1998; Haun & Rapold, 2009). The current findings contradict this claim, converging with previous findings to show that different FoRs can predominate in the same cultural context, in the same person, and even in the same action. We observed this simultaneous mixing of FoRs even in a population with a general preference for one FoR: One quarter of responses by US college students deployed different spatial reference frames on different axes, following the same pattern that predominated among Tsimane' adults and US children (Pitt et al., 2023). The consistency of this pattern across distinct cultures and ages suggests that it may be a universal feature of human spatial cognition.

Role of distance information

In principle, the cross-axis difference reported in previous studies could reflect differential use of distance information (Li & Abarbanell, 2019; Pitt et al., 2022, 2023). Whereas participants standing at a table may encounter some objects on their left and others on their right, all objects on the table are in front of them and none are behind them. Rather, in such tasks, sagittal position is conflated with distance: Some objects are nearer, others are farther. As a consequence, participants might use distance (from themselves) more for sagittal relations than lateral relations, thereby inflating their rate of egocentric responses on the sagittal axis. Yet, there are several reasons to doubt this distance account. First, at the cups level of the 4Quads task, distance information was useful on both the sagittal and lateral axes. Whereas the critical stimuli in previous tasks have been centered in front of the participant, they are placed far out to the sides in our task (see Figure 1). This large rectangular configuration means that, within each quad, participants chose between near and far cups on both the sagittal axis (i.e. 2 rows of 2 cups) and the lateral axis (e.g. the near-left and the far-left columns). Cup-selection based only on distance would result in equal proportions of egocentric and allocentric responses on the lateral axis (i.e. no preference), but this is not what we found. Rather, we found statistically significant FoR preferences on this axis, preferences that went in opposite directions across groups: Tsimane' participants preferred allocentric responses and US participants preferred egocentric responses. Second, studies in another population reveal the same effect of axis on FoR use in a task that fully equates distance. In Pitt et al. (2023), children learned a novel "dance" routine in one of four directions – leftward, rightward, forward, or backward – and then repeated the dance after turning around 180°. In that task, forward and backward dances differed in direction, not distance, making distance information unhelpful on both axes. Yet, participants showed a strong cross-axis reversal in FoR use nevertheless, repeating lateral dances allocentrically and sagittal dances egocentrically, consistent with the pattern of spatial memory observed in Tsimane' adults. If distance information plays any role in these effects, these findings suggest it is a small one.

The role of spatial discrimination

The observed differences in FoR use correspond to known differences in spatial discrimination. Across axes, people use egocentric FoRs more where egocentric discrimination is generally easier – on the sagittal axis. Over developmental time, children increase their use of egocentric space in memory and language as they gradually overcome this mirror invariance, at least in high-literacy cultures (Pitt et al., 2023; Shusterman & Li, 2016; Acredolo, 1978; Blackburne et al., 2014; Kolinsky et al., 2011; Cox & Richardson, 1985). Across cultures, allocentric responding tends to be highest (in both spatial language and memory) in cultures where mirror invariance also remains high (Pitt et al., 2022; Marghetis et al., 2020; Danziger & Pederson, 1998; Pederson et al., 1998; Fernandes et al., 2016). In this way, differences in spatial discrimination are correlated with differences in FoR use across axes, ages, and cultures, offering a compelling potential explanation of spatial cognitive diversity at many levels. To test whether spatial discrimination plays a causal role in FoR use as we hypothesize, future work should experimentally manipulate participants' spatial discrimination abilities through proprioceptive or visuospatial training.

Here we showed systematic differences in FoR use across egocentric axes, but similar differences are likely found across a variety of spatial continua, only some of which are egocentric. For example, Li and Gleitman (2002) showed that changing the salience of allocentric cues (e.g. by opening or closing the window blinds) increased allocentric responding among US college students. Likewise, Brown and Levinson (1993) found that Tenejapan Mayan adults more strongly preferred encoding spatial relations allocentrically when they aligned with salient features of the environment. Such effects are consistent with the Spatial Discrimination Hypothesis, which makes predictions about the *relative* discriminability of competing spatial continua, whether they are egocentric or allocentric.

The tradeoff among candidate FoRs is likely determined both by characteristics of the observer (i.e. a person's physical, perceptual, and cognitive abilities like spatial discrimination) and by the features of their environment, which may vary radically across cultures and contexts. On this account, people prefer using egocentric space to encode spatial relations on the sagittal axis not because of how it compares to the lateral axis, but because of how it compares to the allocentric alternatives that are available to encode that spatial relation, FoRs that might be defined by the features of the room (Li & Gleitman, 2002), the slope of the mountain (Wassmann & Dasen, 1998; Cooperrider, Slotta, & Núñez, 2017), or the position of the sun in the sky (Jang, Boesch, Mundry, Kandza, & Janmaat, 2019).

Spatial thinking in context

Scholars have long asked which FoR people prefer in a given context. However, the current results suggest that this question may be misguided. Rather than thinking egocentrically or allocentrically in a given context, even adults with strong culture-specific spatial conventions nevertheless use multiple reference frames at once. In principle, these hybrid reference frames could be relatively stable across contexts, but we suggest they are highly context specific. On this account, people often improvise the way they encode spatial relations, constructing *ad hoc* reference frames by combining continua available in the local context, whether they are egocentric or allocentric. Even behavior that seems to reflect a single reference frame (e.g. overwhelmingly allocentric responses) may actually reflect multiple idiosyncratic, context-specific reference frames (e.g. uphill-downhill, uptown-downtown, windward-leeward, park bench-duck pond).

This framework can help to explain variability in FoR use both across groups (with different ecological settings and material cultures) and across contexts (with different local affordances). In this way, culture may influence FoR use both by changing people's perceptual abilities (e.g. reinforcing or counteracting mirror invariance) and by shaping the spatial structure of their physical environment (e.g. crop fields, parking lots, floor plans). Only by studying spatial thinking in context can we understand its extraordinary diversity, development, and dynamics.

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