# Multi-directional mappings in the minds of the Tsimane': Size, time, and number on three spatial axes

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## Abstract

From early in life, people implicitly associate time, number, and other abstract conceptual domains with space. According to the *Generalized Magnitude System* proposal, these mental mappings reflect a common neural system for representing various magnitudes, and share a common spatial organization. In a test of this proposal, here we measured mappings of size, time, and number in the Tsimane', an indigenous Amazonian group with few of the cultural practices (like reading and math) that spatialize size, time, and number in the experience of industrialized adults. On three spatial axes, the Tsimane' systematically arranged imagistic stimuli according to their magnitudes, but they showed no directional preferences overall and individuals often mapped different domains in opposite directions. The results are inconsistent with predictions of the Generalized Magnitude System proposal but can be explained by *Hierarchical Mental Metaphor Theory*, according to which mental mappings initially reflect a set of correlations observable in the natural world.

**Keywords:** Metaphor; Magnitude; Spatial cognition; SNARC; Culture

## Introduction

People implicitly associate time, number, and other abstract conceptual domains with space. For example, people implicitly associate smaller numbers with the left side of space and larger numbers with the right side, forming a *mental number line* that increases from left to right, at least among adults in Western industrialized cultures (Dehaene, Bossini, & Giraux, 1993). Likewise, in many cultures people associate earlier events in *time* with the left and later events with the right, forming a *mental timeline* that progresses from left to right (Tversky, Kugelmass, & Winter, 1991). Spatial mappings of non-spatial conceptual domains extend beyond time and number to domains like size (Ren, Nicholls, Ma, & Chen, 2011; Bulf, Cassia, & de Hevia, 2014), loudness (Hartmann & Mast, 2017), and brightness (Ren et al., 2011) on the lateral axis, and such mappings have been found on all three spatial axes: lateral (left-right), vertical (up-down), and sagittal (front-back; e.g. Winter, Matlock, Shaki, & Fischer, 2015; Fuhrman et al., 2011). Where do these mappings come from and how are they related to each other? Two influential theories offer different answers to this question.

On one account, spatial mappings like the mental number line and mental timeline are the product of a shared neural system for representing space, number, and time, as well as other magnitudes. The hypothesized *Generalized Magnitude System* (GMS; Walsh, 2003) is said to represent magnitudes in disparate conceptual domains in a "common underlying code" (Cantlon, Platt, & Brannon, 2009), a domain-general analog magnitude metric for indexing "how much." [1] Some support for this proposal comes from studies of prelinguistic infants, who appear to expect a change in the magnitude of one domain (e.g. size) to correspond to an analogous change in the magnitude of another domain (e.g. duration; Lourenco & Longo, 2010; de Hevia, Izard, Coubart, Spelke, & Streri, 2014).

One of the few "strong predictions" that Walsh (2003) offered in his seminal GMS proposal was that the so-called "mental number line" would prove to be not a mapping of number per se but a mapping of quantity more generally. Since then, other researchers have tested for such a "mental magnitude line" (Holmes & Lourenco, 2011), arguing that by "serving to organize magnitude in a consistent manner...space may serve a fundamental organizational role, extending beyond number to magnitude information more generally. . . " (Lourenco & Longo, 2011). They reason that when a given domain (like brightness or emotional intensity) is mapped in the same direction as one of the "big three" magnitude domains (like number), then this provides "compelling support" (Holmes & Lourenco, 2011) that these domains are all represented by a generalized magnitude system.

On some versions of this account, the GMS causes people not only to spatialize different magnitudes in the *same* direction, but to spatialize them in a *particular* direction: from

[1] This system applies to any domain that can be represented in terms of *more* and *less* relations, but "the big three magnitudes" (Lourenco & Longo, 2011) of size, time and number are the most widely studied.

left to right. As Holmes and Lourenco (2011) argued, "left-to-right orientation may extend to any dimension that can be captured in terms of more/less relations." This proposal finds some support in studies of human infants and non-human animals, which suggest that at least some spatial mappings may have a default left-to-right direction. Monkeys, newborn chicks, and even human neonates appear to associate smaller numbers of objects with the left side of space and larger numbers with the right (Vallortigara, 2018), leading some researchers to posit that "a predilection to map numbers from left to right is embodied in the architecture of all animal neural systems" (Rugani, Vallortigara, Priftis, & Regolin, 2015; see also McCrink & de Hevia, 2018). In short, these accounts posit that various domains – notably spatial, temporal, and numerical magnitude – inherent their shared spatial structure from a common representational system which underlies them all.

On an alternative account, mental mappings of time, number, and other non-spatial domains have distinct origins and can be represented independently. According to theories of metaphoric mental representation, many cross-domain associations reflect *mental metaphors*, point-to-point mappings from a source domain (e.g. space) onto a target domain (e.g. time or numbers), which support inferences in the target domain (Lakoff & Johnson, 1980; Pitt & Casasanto, 2019). On one such account, called *Hierarchical Mental Metaphor Theory* (HMMT; Casasanto, 2017), the mental metaphor linking source and target domains is constructed over two stages. In the first stage, mental metaphors are structured by cross-domain correlations that are observable in the natural world. For example, space and time are correlated in the movement of objects; progress through time corresponds to progress through space. This space-time correlation is found for motion in any direction (e.g. right, left, up, down, etc.) and so it gives rise to a mental metaphor linking progress through time with progress through space *in any direction*. This direction-agnostic mapping between space and time, called the *over-hypothesis*, sits atop the proposed hierarchy of metaphorical mappings and comprises a family of specific mappings (i.e. *specific hypotheses*), including rightward, leftward, upward, and downward mappings, among others (Casasanto & Bottini, 2014).

In the second stage, the overhypothesized family of mappings is shaped by correlations in cultural, linguistic, and bodily experiences. For example, the experience of reading text from left to right provides a correlation between progress through time and progress *rightward* through space; on each line of English text, the reader's gaze starts on the left side at an earlier time and ends on the right side at a later time. As a result of this space-time correlation, which is built into the act of reading and writing text, readers of English accumulate a disproportionate amount of evidence for a rightward-directed mapping of time, whereas readers of Arabic (which is written from right to left) accumulate evidence for a leftward-directed mapping of time. This difference in the way time is spatialized in reading explains cross-cultural variation in the direction of the mental timeline; whereas English- and Dutch-speakers have mental timelines that progress from left to right, Arabic- and Hebrew-speakers show mental timelines that progress in the opposite direction, from right to left (Casasanto & Bottini, 2014; Shaki, Fischer, & Petrusic, 2009). Moreover, spending just a few minutes reading mirror-reversed text (i.e. English written from right to left) can change the direction of people's typical rightward mental timelines (Casasanto & Bottini, 2014; Pitt & Casasanto, 2019). Like the mental timeline, the mental *number* line has a direction that is variable across cultures (Shaki et al., 2009) and sensitive to brief laboratory interventions; experiences that systematically spatialize numbers selectively influence the direction of the mental number line (Pitt & Casasanto, 2019).

These findings show that, whatever their starting point, mappings of time and number can be shaped by cultural practices (like reading and math) that systematically spatialize time and numbers in people's experiences; strong directional practices produce strong directional mappings. For this reason, the GMS proposal is difficult to test in people with strong directional practices like industrialized adults, as their mappings could in principle result from a GMS or from the directional practices of their culture (or both).

Some researchers have studied the mappings of people from indigenous societies, where cultural conventions like reading and math are rare or absent. With no formal schooling, no calendar system, and no words for *time* or *year*, the Amondawa people of Brazil nevertheless showed signs of a horizontal mental timeline, systematically arranging objects that represented events in a temporal sequence (e.g., sowing and harvesting crops; Sinha, Sinha, Zinken, & Sampaio, 2011). Likewise, the Yupno people of Papua New Guinea, who lack writing, calendars, and linear measurement tools, nevertheless spatialized objects in a line according to the size or number they depicted (Cooperrider, Marghetis, & Núñez, 2017, but see Núñez, Cooperrider, & Wassmann, 2012). However, neither group showed any directional preferences in their mappings. Rather, mappings varied widely in direction, even among people with the same language and culture.[2] Although these previous studies suggest that such mappings do not have a default direction (e.g. left-to-right), they do not address the basic GMS proposal (nor were they designed to), according to which different mappings should have the same direction *in a given mind*. Indeed, the direc-

[2] In another study (Núñez, Cooperrider, Doan, & Wassmann, 2012), the Yupno systematically associated future events with the uphill direction and past events with the downhill direction (see Boroditsky and Gaby (2010) for another *allocentric* mapping of time). This spatial mapping of *deictic* time (e.g. yesterday, today, tomorrow) is not relevant to the GMS. Whereas the GMS proposal applies only to *prothetic* domains (i.e., domains in which people experience quantitative variation, as in numerical cardinality or temporal duration), deictic time is an example of *metathetic* domain (i.e., a domain in which people experience qualitative variation; Stevens, 1957); an hour has more time than a minute but *tomorrow* does not have more time than *today*.

tion of different mappings could be highly consistent *within* individuals even if it were highly variable *across* individuals. Therefore, evaluating this central prediction of the GMS proposal requires comparing mappings of different magnitudes within individuals.

Here we conducted within-subjects tests of size, time, and number mappings in the Tsimane', a group of farmer-foragers indigenous to the Bolivian Amazon (Huanca, 2008). With little or no formal education, Tsimane' adults have low literacy levels and many have only basic numerical abilities, often struggling to perform simple addition problems (O'Shaughnessy, Gibson, & Piantadosi, forthcoming). Computers, cell phones, printed materials, and other modern technologies are uncommon. The result is a material culture that is largely devoid of the kinds of cultural practices and artifacts that spatialize time, numbers, and other quantities in a consistent direction in the experience of industrialized adults.

We tested each participant on all of the "big three" magnitude domains – size, time, and number – on all three spatial axes: lateral, vertical, and sagittal. On each axis, they arranged sets of five cards in a line according to the spatial, temporal, or numerical magnitudes that the cards depicted (see Figure 1). A fully within-subjects design allowed us not only to measure the overall directional biases of the group, but also to compare the directions in which individual participants spatialized different domains on each axis.

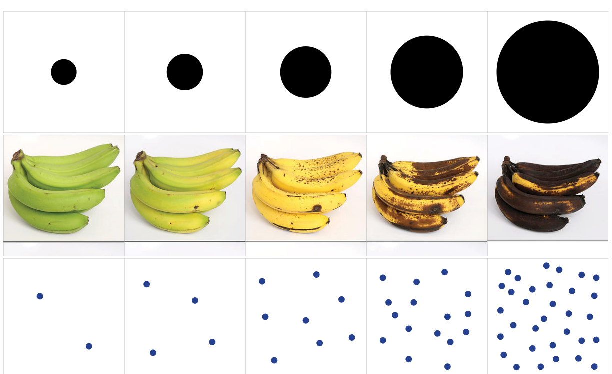

Figure 1: Stimuli for size, time, and number tasks, here shown with magnitude increasing from left to right.

The theories outlined above make contrasting predictions about the way the Tsimane' should spatialize size, time, and number. According to the generalized magnitude system proposal, a mental magnitude line should produce mappings with "a consistent spatial orientation" (Holmes & Lourenco, 2011); a person's mappings of size, time, and number should all go in the *same direction* on a given spatial axis, whatever direction that may be. However, if left-to-right orientation is a general "property of magnitude representation" (Holmes & Lourenco, 2011), as some GMS theorists have proposed, then Tsimane' participants should not only map different domains in the same direction, they should map them from left to right by default. By contrast, if strong directional mappings result from strong directional practices, then people who rarely engage in practices that consistently spatialize size, time, or numbers should not have strong culture-specific mappings of those domains, nor should they necessarily map different domains in the same direction. Rather, according to Hierarchical Mental Metaphor Theory, they should have the overhypothesized, direction-agnostic mappings that are observable in the natural world. On this account, given that the Tsimane' lack strong directional practices, they should produce mappings that are *systematic*, with smaller magnitudes closer to one pole and larger magnitudes closer to the other pole in any one mapping, but the direction of these mappings may differ within and across individuals.

## Method

### Participants

Sixty Tsimane' adults provided informed consent and participated in exchange for goods. All protocols were approved by the IRB of UC Berkeley.

### Materials

We constructed three sets of five cards, one set for each of the three tasks (see Figure 1). In the size task, each card showed a single black circle whose area differed by factors of two. In the time task, cards depicted a bunch of bananas of various ages, from under-ripe to rotten. In the number task, each card showed an array of dots (i.e. a "dot cloud"), and the number of dots differed across cards by factors of two, from 2 to 32. On the back of each card (approximately 3x3 inches, laminated), we placed an adhesive piece of velcro which allowed the card to be temporarily affixed to a velcro board. Velcro boards were 3x24 inches and had a strip of velcro adhered lengthwise along the middle of the board. Three identical velcro boards were used, one for each spatial axis (to avoid translating a single board between spatial axes in view of participants).

### Procedure

Each participant performed all three tasks (size, time, and number) on each spatial axis (lateral, vertical, and sagittal) before progressing to the next axis, for a total of nine trials. The order of spatial axes was counterbalanced across participants and the order of tasks on a given axis was quasi-randomized.

Participants were seated at a table between the experimenter and translator (such that all three were on the same side of the table). Two of the velcro boards were positioned on the table, one oriented laterally to the participant and the other oriented sagittally. The third velcro board was oriented vertically (i.e. resting on its short side) on a chair beside the participant.

For each task, participants were presented with all 5 cards, which the experimenter placed in a disordered pile on the table or chair near the relevant velcro board. After explaining how the five cards differed from each other (in size, age, or


Figure 2: A translator explains the size task to a Tsimane' woman.

number), the experimenter picked up the card depicting the "medium" magnitude and placed it in the middle of the velcro board (and explained this action verbally; see Figure 2). Participants were instructed to "organize the other cards on the board in order of their size/age/number." Once the participant was done placing all the cards on the board, the experimenter noted the position of each card, without providing any feedback to the participant. After each task on the first axis, the experimenter also asked the participant to indicate which card had the smallest circle, the newest bananas, or the fewest dots and then to indicate which card had the largest circle, the oldest bananas, or the most dots. All cards were removed from the velcro board after each trial. After completing all three tasks on a given axis, the velcro board for that axis was removed from sight and the participant was directed to the board that corresponded to the next axis.

## Results

### Coding

The systematicity and direction of each mapping was calculated using Kendall's Tau, which yielded a score between 1 and -1 (see Figure 4). The sign of this score indexes the *direction* of the mapping: Positive mappings were those in which magnitudes generally increased rightward, upward, or away from the participant; negative mappings were those in which magnitudes generally increased leftward, downward, or toward the participant. The absolute value of the score indexes the *systematicity* of the mapping (i.e. how orderly it was): A score of +/-1 corresponds to a perfectly systematic mapping; one in which magnitude increased monotonically in one direction across all five cards. Intermediate scores reflect imperfectly ordered mappings of magnitude. For example, a score of 0.8 corresponds to a mapping with a strong rightward trend with one *swap* (i.e. two adjacent cards whose positions could be reversed to produce a perfectly ordered mapping). A score of zero corresponds to a mapping with no systematicity and therefore no discernable direction.

### Exclusions

Participants correctly identified which two cards depicted the most extreme magnitudes in 88% of trials. For tasks on which they failed (12%), their data for that task was excluded for all spatial axes.

### Systematicity of mappings

Overall, across all domains and axes, participants produced perfectly systematic mappings in 52% of trials and nearly perfect mappings (i.e. with only one *swap*) in another 11% of trials. Figure 3 shows the distribution of mapping scores for each domain and each axis. The observed distributions differed significantly from the chance distribution (i.e. the distribution of mapping scores that would result from random spatial arrangements) for all domains on all axes (according to Kolmogorov-Smirnov tests; all $p's < .0001$). Participants used space systematically to organize the stimuli according to their relative magnitudes.

As shown in Figure 3, the distribution of mapping scores was trimodal, with peaks at each extreme and a peak in the middle near zero. We used this attribute of the data to distinguish systematic mappings (i.e. those with scores more extreme than +/- 0.5) from unsystematic mappings (i.e. with scores between -0.5 and +0.5). Because unsystematic mappings do not have clear directionality, they are excluded from the following analyses (and from Figures 5 and 6), which test directional patterns within and across individuals.

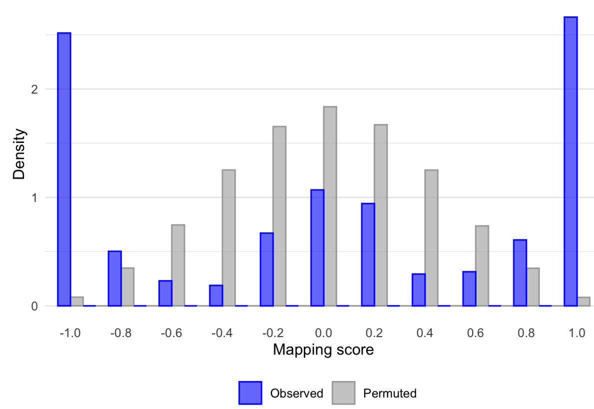


Figure 3: Systematicity of all mappings. The observed distribution of mapping scores (blue bars) differed significantly from the null distribution overall (grey bars) for all domains and axes.

### Directional biases at the group level

To test for directional preferences in our sample of participants, we calculated the proportion of mappings that went in each direction (i.e. positive or negative) on each axis and compared this proportion to chance (50:50). Across all three domains and spatial axes, participants showed no reliable directional preferences; binomial tests with Bonferroni correc-

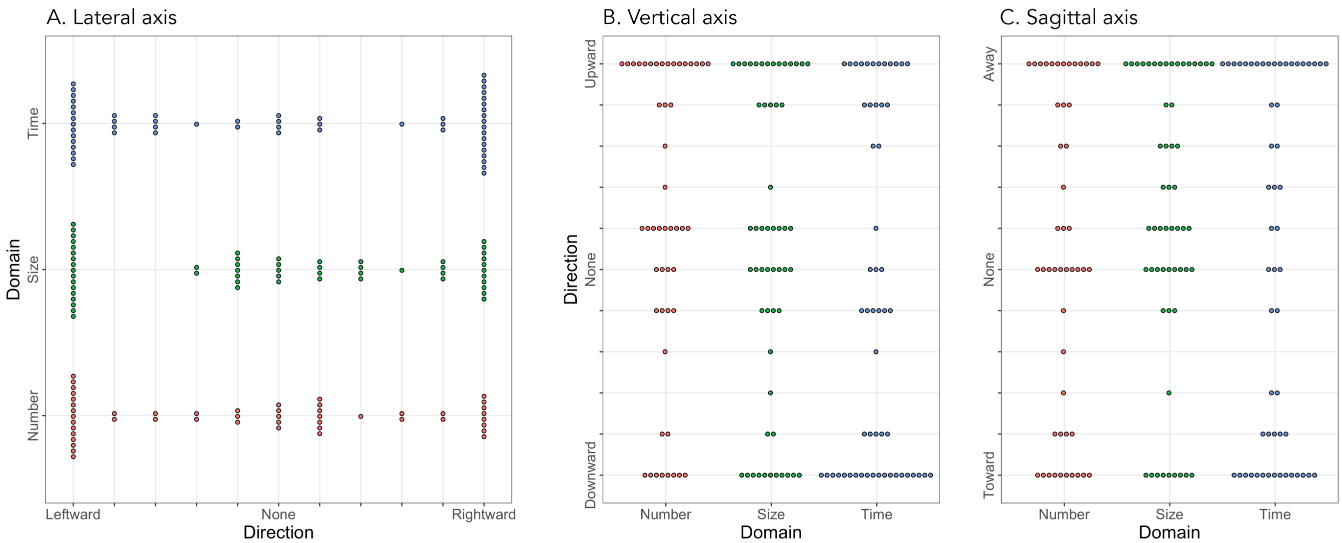


Figure 4: All mappings, by axis and task. Dots closer to the poles represent more systematic mappings, and different poles correspond to different directions.

tion showed that the ratio of positive and negative mappings did not differ reliably from chance (all $p's > .05$). Rather, participants produced roughly equal numbers of positive mappings and negative mappings, as seen in Figures 4 and 5.

Notably, there was no evidence of a left-to-right mapping of numbers. In fact, participants produced more leftward mappings than rightward mappings of number (although the trend was not statistically significant; see shortest bar in Figure 5).

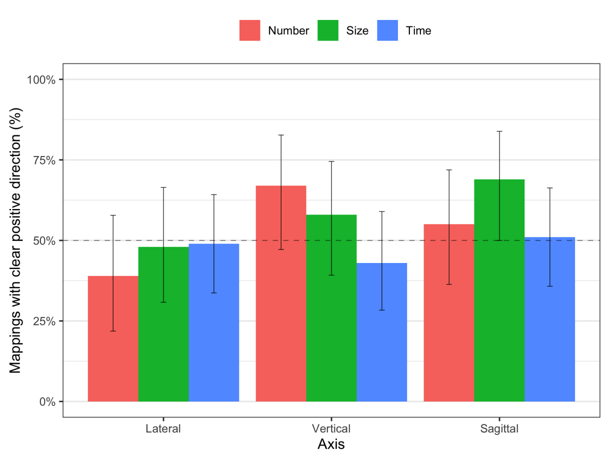


Figure 5: Proportion of positive mappings of each domain on each axis. Positive mappings were those that went clearly rightward, upward, or away. Error bars show 95% confidence intervals.

## Directional consistency of individuals

The within-subjects design of this experiment allowed us to test the extent to which individual participants mapped different domains in the same direction or in different directions on a given spatial axis. We compared the direction of mappings across each pair of domains, as shown in Figure 6. Overall, 64% of mappings went in the same direction and 36% of mappings went in opposite directions. Across axes, participants were most consistent in the way they mapped size and numbers, arranging them in the same direction 80% of the time and in opposite directions 20% of the time ($p < .0001$; Figure 6, left). Participants showed less consistency between size and time (61% same direction; $p = .05$; Figure 6, center) and between time and numbers (53% same direction; $p = .67$; Figure 6, right), neither of which patterned together significantly more than would be expected by chance (according to Bonferroni-corrected binomial tests). Whereas size and numbers reliably patterned together on all three axes (even with Bonferroni correction; all $p's < .01$), no other pair of domains was more consistent in direction than would be expected by chance, on any axis (all $p's > .10$).

# Discussion

People map size, time, number, and other domains onto space, and this widespread cognitive tendency has often been attributed to a Generalize Magnitude System (Walsh, 2003; Bueti & Walsh, 2009), a single neural system for representing magnitudes across various domains. Here we tested a central prediction of the GMS account by studying the spatial mappings of size, time, and number in the Tsimane', an indigenous society with little exposure to the cultural practices that spatialize these domains in the experience of industrialized adults. The Tsimane' showed no overall directional preference for any domain on any spatial axis, and individuals often spatialized different domains in different directions on a given axis.

The results are inconsistent with central predictions of the GMS proposal. On one version of this proposal, people

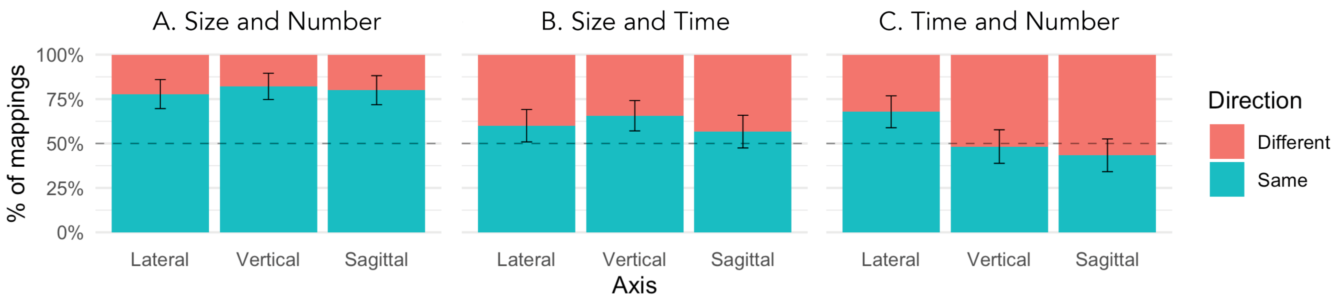


Figure 6: Consistency of mapping direction across each pair of domains.

should spatialize size, time, number and "any dimension that can be captured in terms of more/less relations" (Holmes & Lourenco, 2011) from left to right, by default. The Tsimane' showed no evidence of this pattern for any of the "big three" domains, producing as many leftward mappings as rightward mappings. This finding in adults is at odds with some studies of human infant and non-human animals, which suggest that a left-to-right mapping of numbers may be biologically endowed (Vallortigara, 2018; Rugani et al., 2015, but see McCrink & de Hevia, 2018).

These findings also bear on one of the "strong predictions" (Walsh, 2003; Bueti & Walsh, 2009) of the GMS proposal, a prediction that has motivated tests of the GMS since its inception: mappings should have "a consistent spatial orientation" (Lourenco & Longo, 2011) across domains along a purported "mental magnitude line" (Holmes & Lourenco, 2011). Indeed, GMS theorists have often interpreted the directional consistency observed in industrialized groups as "compelling evidence" for a GMS (Holmes & Lourenco, 2011; but see Pitt & Casasanto, 2018; Casasanto & Pitt, 2019). However, many of those effects can also be explained by direction-specific cultural practices (like reading and math) which tend to go in the same direction in a given culture. Here we showed that people without strong directional practices show little consistency in their spatial mappings: In more than one third of trials, individual participants arranged size, time, and number in opposite directions.

This pattern of findings cannot be explained by a GMS, but it can be explained by Hierarchical Mental Metaphor Theory.[3] According to the CORrelations in Experience (CORE) principle, one of the central tenets of HMMT, people map a given domain in their mind according to the way that domain is spatialized in their experience (Pitt & Casasanto, 2019). Therefore, in industrialized societies where size, time, and number tend to be spatialized in the same direction (e.g. from left to right), people should map all three domains in the same direction. Broad support for this prediction of HMMT comes from cross-cultural comparisons of spatial mappings (e.g. Tversky et al., 1991) as well as from causal interventions in the lab that selectively manipulate the spatialization of individual domains in people's experience (Pitt & Casasanto, 2019).

Beyond explaining the directions of spatial mappings within and across industrialized cultures, HMMT also explains the present findings in the Tsimane'. The Tsimane' have less experience with the cultural practices that consistently spatialize size, time, and number in industrialized societies (like reading and math), but they have ample experience with the space-size, space-time, and space-number correlations that are observable in the natural world. For example, space and time are correlated in the motion of objects, whichever way they travel. Likewise, arrays of objects get longer in space (on average) as they become more numerous, providing a correlation between space and number that applies in any direction. To the extent that these correlations are similarly prevalent in any direction, they should give rise to direction-agnostic mappings of these domains.[4] The multidirectional mappings we observed in the Tsimane' do not reflect a generalized magnitude system but may reflect the overhypothesized mappings that HMMT posits, the results of the first stage in the process of constructing mental metaphors.

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[3] To be clear, these findings do not rule out an alternative version of the GMS proposal, one which does not make predictions about spatial mappings at all. In principle, people could associate more in one domain with more in another domain, as the GMS posits, even if such associations had no effect on the spatial mappings of those domains. However, the current findings challenge the claim that a common code for representing magnitudes underlies people's mappings of size, time, and number, a claim that has animated empirical tests of the GMS proposal since its inception (Walsh, 2003; Bueti & Walsh, 2009)

[4] In principle, correlations in the natural world can be stronger in one direction than in others. For example, Lakoff and Johnson (1980) suggested that people may have a universal 'More is Up' metaphor as a result of the universal correlation between quantity and vertical height given by the natural world: Piles get taller as more quantity is added. We found no evidence of such a mapping.

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