Spatial concepts of number, size, and time in an indigenous culture

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In industrialized groups, adults implicitly map numbers, time, and size onto space according to cultural practices like reading and counting (e.g. from left to right). Here we tested the mental mappings of the Tsimane', an indigenous population with few such cultural practices. Tsimane' adults spatially arranged number, size, and time stimuli according to their relative magnitudes but showed no directional bias for any domain on any spatial axis; different mappings went in different directions, even in the same participant. These findings challenge claims that people have an innate left-to-right mapping of numbers and that such mappings arise from a domain-general magnitude system. Rather, the direction-specific mappings found in industrialized cultures may originate from direction-agnostic mappings that reflect the correlational structure of the natural world.

In many cultures, people reason about number, time, and other conceptual domains using space. For example, Americans and Europeans implicitly associate smaller numbers with the left side of space and larger numbers with the right side, forming an implicit *mental number line* (1, 2). Although the mental number line has been the subject of hundreds of studies (3), its phylogenic origins remain controversial. Some scholars have proposed that a left-to-right mapping of number may be innate, based on studies of human infants and non-human animals like monkeys, chicks, and fish (4–8). For example, after habituating to visual arrays with a fixed number of dots, human neonates looked to the left in response to smaller numbers of dots and to the right in response to larger numbers (9). Innate left-to-right mappings may not be unique to number (10). On some accounts, number shares representational structure with other conceptual domains, including time and size, as part of a *Generalized Magnitude System* in parietal cortex (11–14). On the strongest versions of this theory, the mental number line is a manifestation of a domain-general *mental magnitude line* which provides common spatial structure to mappings of number, size, and time, among others (15, 16). If so, then any spatial biases in number mappings should also be found for mappings of these other domains.

These proposals are difficult to test in industrialized groups, where any innate spatial biases may be masked by or confounded with cultural conventions that cause number, time, and other domains to be spatialized in a consistent direction (e.g. reading and counting from left to right). Such conventions are enough to influence mental mappings of these domains, which vary in direction with spatial practices like reading (17–19) and which can be independently changed by brief spatial training (20, 21). These effects support theories of metaphorical mental representation positing that each mental mapping arises from the correlations between the relevant domains (e.g. space and number; space and time) that are found in the natural and cultural environment (21–23). On this alternative account, direction-specific cultural experiences act on mental mappings that initially lack specific direction (20).

To isolate effects of cultural experience, we tested mental mappings in the Tsimane', an indigenous group of farmer-foragers who live in the Amazon basin of Bolivia (24). With little or no formal education, low levels of literacy and numeracy, and few modern technologies (25,26), many Tsimane' adults have scant experience with the directional practices that may mask innate spatial biases in industrialized cultures. Therefore, if mental mappings of number (or other domains) have rightward direction by default, then unindustrialized groups like the Tsimane' should show this spatial bias (27–30).

Figure 1: Materials. In Experiment 1 (left), participants arranged stimuli that varied in (A) number and (B) size. In Experiment 2 (right), participants arranged (C) size, number, and time stimuli on all three spatial axes. (D) A translator explains the size task (on the lateral axis) to a Tsimane' woman.

In Experiment 1, we tested number and size mappings in Tsimane' adults by having them manually arrange stimuli that varied in number (1-5 dots) or size (1-5 inches) along a lateral response array, as shown in Figure 1, left (31). We included comparison groups of US adults, who have extensive experience with left-to-right cultural practices, and of US children (ages 3-5), who have relatively little such experience. If people have an innate predisposition to map numbers or other magnitudes from left to right, then those spatial biases should be evident in all three groups. Figure 2 shows the distribution of mapping scores that each group (columns) produced for each domain (rows), contrasted with the chance distribution (in grey). US adults

showed a strong rightward bias in their mappings; both number and size increased monotonically from left to right in every case. By contrast, Tsimane' adults and US children showed no such bias for number or size (whether these domains were analyzed separately or pooled together). Rather, participants were equally likely to map the stimuli to the left as to the right, as shown by their response histograms with peaks near the extremes. The dot and whiskers on each plot show that, on average, these mapping scores did not differ significantly from zero. We found the same result when analyzing only the mappings with clear directionality, excluding mappings with scores near zero. Only the most educated of our Tsimane' participants showed any sign of a rightward bias in either domain (see Figure 6 in Supplementary Text).

In principle, participants could have shown no systematic use of space at all, arranging the stimuli without respect to their relative magnitudes. This was not the case; for every group and domain, the observed distribution of mappings (i.e. colored bars) differed significantly from the chance distribution (i.e. grey bars). For example, whereas randomly arranging the stimuli will result in a perfectly monotonic array only 1.5% of the time by chance, participants produced such arrays 47-100% of the time on average. Therefore, the lack of directional bias in US children and Tsimane' adults cannot be explained by a misunderstanding of the task or by an absence of spatial associations; both groups systematically ordered the stimuli according to their relative magnitudes, in one direction or the other.

These findings challenge claims that people have an innate predisposition for left-to-right mappings of magnitudes generally (15) or of numbers specifically (9). If children started with an innate rightward bias, then enculturating them with clear rightward spatial conventions should only *strengthen* such mappings (32). Yet, here US children showed *no* rightward bias, despite the spatial conventions of American culture (32–34). Likewise, if direction-specific cultural conventions changed or masked innate spatial biases (5), then people without such conventions should retain those biases. Yet, here Tsimane' adults showed no evidence of a default rightward

Figure 2: Lateral number and size mappings in three populations. Mappings ranged from perfectly leftward to perfectly rightward, with less orderly mappings in the middle. Colored bars show participants’ mappings of number (blue) and size (pink), which differed significantly from chance (grey). Black dots and whiskers show mean mapping scores and uncorrected 95% confidence intervals.

bias in their mappings (27). Therefore, the lack of directional biases among US children and Tsimane’ adults cannot reflect displacement of innate rightward biases. Rather, these findings support the proposal that the direction of lateral mappings is determined by direction-specific experiences, like those that are common in industrialized cultures (21, 22).

Even if the hypothesized mental magnitude line does not have any default direction, it could nonetheless provide a common spatial structure to different mappings *in a given mind*. Indeed, this is one of the “strong predictions” (11) of the generalized magnitude system proposal; different mappings should share a common direction (15, 16). To clarify the links between different mappings in a given mind, Experiment 2 tested a new group of Tsimane’ adults (N = 60) on their mappings of all three of the magnitude domains central to the generalized magnitude system proposal – size, number, and time (see Figure 1: C; (16)). We also expanded our testing to include all three spatial axes: lateral, vertical, and sagittal (i.e. front-back), where mental

mental mappings of number (and other domains) have been observed (31, 35–37). In principle, the lack of directional bias observed in Experiment 1 could be unique to left-right space, which is more difficult for people to distinguish than up-down or front-back space (38–40), and which may be especially difficult in unindustrialized groups like the Tsimane’ (41, 42). We therefore tested participants’ mappings of all three conceptual domains on all three spatial axes. This fully within-subject design allowed us not only to compare mapping direction across individuals (27, 28, 37), but also across domains *within* individuals. To ensure that participants could accurately compare the magnitudes of each stimulus set as intended, we asked them to identify which stimulus in each set was biggest/most/oldest and which was smallest/least/newest and we excluded mappings (12%) for which participants did so incorrectly (43).

Figure 3 shows the distribution of mappings that participants produced for each domain on each spatial axis. As in Experiment 1, participants’ mappings (i.e. colored bars) differed significantly from the chance distribution (i.e. grey bars), indicating that participants arranged the stimuli in space according to their relative magnitudes, as instructed. Yet, despite this systematicity, they showed no directional biases on any spatial axis for any domain (whether number, size, and time were analyzed separately or pooled together), replicating the results of Experiment 1 and extending them to the domain of time and to the vertical and sagittal axes. The dots and whiskers in Figure 3 show the means and uncorrected 95% confidence intervals of each mapping on each axis; none reliably differed from zero (when correcting for multiple comparisons). We found the same result when analyzing only mappings with clear directionality, excluding mappings with scores near zero; for all three domains on all three axes, the Tsimane’ used space systematically but showed no directional biases.

Using this same subset of mappings, we evaluated directional consistency *within* participants by doing pairwise comparisons among the three mappings each participant produced on a given axis, as shown in Figure 4. If these mappings were manifestations of a single mental

Figure 3: Number, size, and time mappings on three spatial axes. Mappings ranged from perfectly negative (i.e., leftward, downward, or toward) to perfectly positive (i.e., rightward, upward, or away), with less orderly mappings in the middle. Colored bars show participants' mappings of number (blue), size (pink), and time (green), which differed significantly from chance (grey). Black dots and whiskers show mean mapping scores and uncorrected 95% confidence intervals.

magnitude line, then any coherent mappings that a participant produced should have gone in the same direction. Contrary to this prediction, participants mapped all three domains in the same direction in only 42% of cases; in all other cases, participants arranged stimuli systematically (i.e. in order) but in *opposite* directions. Across axes, number and size mappings were most consistent in direction (80% same direction; 95%*CI* : 0.70 – 0.87), whereas size and time patterned together in 61% of cases (95%*CI* : 0.51 – 0.70) and time and number patterned together in only 53% of cases (95%*CI* : 0.42 – 0.63). It may be unsurprising that number and size mappings were the most aligned, given that these domains are correlated in the natural world

(i.e. greater numbers of objects occupy more space; (44)) as in our experimental stimuli, and that the Tsimane’ describe numbers in terms of size in their language, as in English (i.e. a “big” or “small” number). Nevertheless, participants produced mappings with opposing directions for every set of domains on every axis (Figure 4).

Figure 4: Consistency of mapping direction across each pair of domains. Error bars show the standard error of the mean.

These results challenge existing theories of mental mappings, in two ways. First, the results in Tsimane’ adults and US children are at odds with the proposal that people are born with a left-to-right mapping of number, as suggested by behavioral effects in human infants and non-human animals (4–8). Those effects may reflect hemispheric specialization for spatial frequency (45) or emotional motivation (8), rather than spatial-numerical associations. Second, the mappings we observed cannot be explained by a mental magnitude line, even one without a default direction. If different mappings reflected “the same coordinate system applied to all magnitudes” (12), then any coherent spatial mappings should have had the same direction in a given mind (11, 15, 16). They did not; even the most systematic mappings of size, time, and number regularly went in different directions in the same participant. Therefore, although a generalized magnitude system may explain why people tend to associate more in one domain with more in another (46, 47), it does not explain the way people map domains onto space.

Why did participants’ mappings have coherent spatial structure but lack consistent direction? In principle, each mapping could have a stable direction independent of other mappings,

but it is unclear why it would vary across domains and individuals, given the shared language and culture of our participants. Rather, each mapping may begin without specific direction, as proposed by a theory of metaphorical mental representation (22). On that account, mental mappings arise from cross-domain correlations that are observable in the natural world, like that between space and time: As objects travel further in space, more time passes. Because this correlation applies equally in all directions, it yields mental mappings in all directions. From this direction-agnostic starting point, cultural experiences like reading text or solving equations provide space-time and space-number correlations that are direction-specific (e.g. left to right) and therefore result in the direction-specific mental mappings observed in industrialized groups (20, 21, 48). In this way, culture-specific mental mappings like the left-to-right mental number line may originate from multi-directional mappings that reflect the correlational structure of the natural world.

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2 Supplementary materials

Materials and methods

Supplementary text

2.1 Materials and Methods

2.1.1 Experiment 1

Participants. Tsimane' adult participants were 96 adults (age range: 17-78 years; mean age = 31.63 years, standard deviation = 13.67 years). Participants were recruited from Tsimane' communities near San Borja, Bolivia. All guidelines and requirements of the University of Rochester's Research Subjects Review Board were followed for participant recruitment and experimental procedures. Interpreters were provided by the Centro Boliviano de Investigación y de Desarrollo Socio Integral.

US Children participants were 31 children (age range: 3-5 years; mean age = 4.23 years, standard deviation = 0.69 years). Participants were recruited through the Kid Neuro Lab at the University of Rochester. All guidelines and requirements of the University of Rochester's Research Subjects Review Board were followed for participant recruitment and experimental procedures.

US adult participants were 18 adults (age range: 29-50 years; mean age = 36.17 years, standard deviation = 4.64), who were the parents of the child participants. All guidelines and requirements of the University of Rochester's Research Subjects Review Board were followed for participant recruitment and experimental procedures.

Materials. We constructed two sets of five wooden blocks, one set for number task and one set for size task (see Figure 1: A, B). In the number task, the blocks were all the same height

and were painted white. Each of the number blocks had a number of uniform sized black dots (from 1-5 dots) positioned randomly on the top face. In the size task, the blocks each varied in height (from 1 to 5 inches in increments of 1 inch). All of the blocks in both conditions were 2 inches wide by 2 inches deep. A wooden board with five equally spaced depressions (1/4 inch deep) was constructed such that each of the five blocks could be placed securely in a depression.

Procedure. Each participant performed two tasks (size and number) on a lateral axis. The order of the tasks was counterbalanced across participants. For each task, participants were seated directly across from the experimenter. The wooden board was placed in front of the participant and the five blocks in the first task were presented just behind the board in a random array.

For each task, the experimenter picked up the middle block (3 dots or 3 inches tall) and placed it in the middle position on the board. As the experimenter placed the block, the subject was told “This is the 3rd block. It goes here. The experimenter then picked up the first block (1 dot or 1 inch tall) and handed it to the subject directly over the center of the board, and said: “This is the first block. It goes in the first position.” Participants then placed the block on the board without feedback. This procedure was repeated for the 2nd, 4th, and 5th blocks, until all positions were filled. The order of the tasks was counterbalanced across participants.

2.1.2 Experiment 2

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: C). 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. (A subset of participants (N=18) received an alternative set of time and number stimuli, which are shown in Figure 5. Mapping direction did not differ as a function of stimulus variant for either number or time ($ps > .5$), so these variants were pooled and analyzed together.) 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).

Figure 5: A subset of participants received this alternate set of number and time stimuli.

2.1.3 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 of the given set differed from each other (in size, age, or 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, without naming the card’s ordinal position; see Figure 1: D). 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.

2.2 Supplementary Text

All data and analyses are available at osf.io/7z4mc/

2.2.1 Results of Experiment 1

2.2.2 Coding

The systematicity and direction of each mapping was calculated using Kendall’s Tau, which yielded a score between -1 and 1. The sign of this score indexes the *direction* of the mapping: Magnitudes generally increased rightward in positive mappings, and leftward in negative mappings. 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 positions. 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.

2.2.3 Systematicity

In the control group, all 18 US adults showed perfect systematicity, arranging the number stimuli and the size stimuli in perfect monotonic order. US children and Tsimane' adults were more variable, producing some arrays in which number and/or size did not change monotonically across the array. To determine how systematically each group spatialized each domain, we compared the distribution of mapping scores they produced to the distribution of mapping scores that would be expected by chance (i.e. as a result of random arrangements of the 4 stimuli placed by participants). As Figure 2 shows, the observed distribution of number mappings (blue bars) and size mappings (green bars) differed significantly from the chance distribution (grey bars) in all three groups (according to Kolmogorov-Smirnov tests; all $ps < .0005$); Participants used space systematically to organize the stimuli according to their relative magnitudes.

2.2.4 Direction

To test for directional preferences in each group of participants, we used a simple t-test to compare their mapping scores against zero. The mean direction scores (and 95% confidence intervals) appear as dots and whiskers in Figure 2. In the control group, all 18 US adults produced perfect left-to-right mappings of both size and number ($p \approx 0$). By contrast, Tsimane' adults showed no directional bias for number ($t(95) = -.02, p = .98$) or for size ($t(95) = .71, p = .48$), nor did our group of US children (number: $t(30) = 1.74, p = .09$; size: $t(30) = .54, p = .59$). The same pattern obtained when pooling number and size mappings together for both Tsimane' adults ($t(191) = .48, p = .63$) and US children ($t(61) = 1.61, p = .11$).

Tsimane’ adults and US children did not differ from each other in their mappings of number ($t(50.77) = -1.53, p = .13$) or size ($t(49.42) = -0.13, p = .89$), but both groups differed significantly from US adults in both domains ($ps < .001$).

Although participants were highly systematic in their responses overall, a subset of mappings was disordered with respect to stimulus magnitude, yielding mapping scores near zero. In principle, these disordered mappings, which may have resulted from confusion or inattention, could mask directional biases in the more systematic mappings. To test this possibility, we also analyzed only the mappings of Tsimane’ adults and US children that had clear directionality. Specifically, we excluded the middle half of mapping scores, analyzing only mappings with scores below -0.5 or above +0.5. This cutoff was determined by the distribution of mapping scores in those groups, which was trimodal, with peaks at each extreme, a peak in the middle near zero, and troughs near -0.5 and +0.5 (see Figure 2). The results were the same; neither Tsimane’ adults nor US children showed any directional biases (all $ps > .05$).

2.2.5 Effects of education

By hypothesis, the more exposure a person has to cultural practices that systematically spatialize number and size from left to right, the more likely that person should be to show rightward mental mappings of these domains. We tested for this effect of experience in our group of Tsimane’ adults by evaluating the relationship between their years of formal schooling and their mappings of number and size. For both domains, schooling was a weak but significant predictor of participants’ mappings; Tsimane’ adults with more years of formal schooling were more likely to produce rightward-biased mappings of number ($F(1, 94) = 5.876, p = .02, \beta = .10$) and size ($F(1, 94) = 3.792, p = .05, \beta = .08$), as shown in Figure 6.

We performed an analogous test in our group of US children, using age to predict the strength and direction of their number and size mappings. We found no such effect of age

Figure 6: In Experiment 1, Tsimane' adults with more schooling produced mappings that were more rightward in direction.

($ps > .3$), perhaps because of the limited age range we tested.

2.2.6 Results of Experiment 2

2.2.7 Coding

The systematicity and direction of each mapping was calculated in the same way as in Experiment 1, using Kendall's Tau to produce a mapping score between -1 and 1 on each axis. In positive mappings, magnitude tended to increase rightward, upward, or away from the participant; in negative mappings, magnitudes tended to increase leftward, downward, or toward the participant.

2.2.8 Exclusions

Participants correctly identified which two cards depicted the most extreme magnitudes in 75% of trials, incorrectly identified them in 12% of trials, and were not tested in 13% of trials (43). For tasks on which they failed, their data for that task was excluded for all spatial axes.

2.2.9 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 $ps < .001$). Participants used space systematically to organize the stimuli according to their relative magnitudes.

2.2.10 Directional biases at the group level

To test for directional preferences on each axis, we again used a simple t-test to compare mapping scores against zero. The mean direction scores and 95% confidence intervals appear in Figure 3. Size mappings on the sagittal axis trended away from participants ($t(54) = 2.44, p = .02$) and number mappings on the vertical axis trended upward ($t(48) = .201, p = .05$), but neither trend was significant when correcting for multiple comparisons (which sets $\alpha \approx .01$). No other mappings on any spatial axis showed a direction bias that approached statistical significance (all $ps > .10$). The same pattern obtained when pooling number, size, and time mappings together on each axis ($ps > .05$) and when analyzing only mappings with clear directionality ($ps > .05$), as in Experiment 1.

2.2.11 Directional consistency within individuals

To test the directional consistency of mappings within individuals, we compared the direction of mappings across each pair of domains on each axis for each participant, using only mapping with clear directionality (i.e., excluding mappings with scores between -0.5 and +0.5). If these mappings of size, time, and number were generated by a single mental magnitude line, then they should have the same direction in a given mind. However, participants mapped all three domains in the same direction only 42% of the time (95%*CI* : 0.42 – 0.54) and in different directions the other 58% of the time. Collapsing across axes, participants produced mappings with the same direction for 80% of their size and number mappings (95%*CI* : 0.70 – 0.87), 61% of their size and time mappings (95%*CI* : 0.51 – 0.70), and 53% of their time and number mappings (95%*CI* : 0.42 – 0.63). Only number and size patterned together more than would be expected by chance, which they did on all three spatial axes (p s < .005). According to a generalized linear model, number and size mappings also went in the same direction more often than time and number mappings (p = .0003) and more than size and time mappings (p = .007), whereas the these latter pairs of mappings did not differ from each other in directional consistency (p = .28).

2.2.12 Effects of education

On the lateral axis, participants with more years of schooling made more rightward-directed mappings when pooling all three domains together ($F(1, 149) = 3.95, p < .05$), but this trend did not reach statistical significance for any individual domain (all p s > .10), nor for any domain on the vertical or sagittal axis (all p s > .50).

2.2.13 Linguistic metaphors for number in Tsimane’

A separate group of Tsimane’ adults performed a language elicitation task in which they described (in Tsimane’) the difference between pairs of objects. When asked to compare two sets of identical objects that differed in number, a subset of participants used words meaning small (*miquis*) and large (*därsi*), the same words they used to describe individual objects that differed in physical size (but not in number). Others used words meaning less (*miqui*) and more (*där*), which are close phonetic relatives of the words for small and large in Tsimane’, unlike in English.