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Authors
Marghetis, Tyler
Eberle, Luke C
Bergen, Benjamin K

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The mental number-line spreads by gestural contagion

Tyler Marghetis
tmarghet@ucsd.edu
Department of Cognitive Science
University of California, San Diego

Luke C. Eberle
leberle@ucsd.edu
Department of Cognitive Science
University of California, San Diego

Benjamin K. Bergen
bkbergen@ucsd.edu
Department of Cognitive Science
University of California, San Diego

Abstract

Mathematical expertise builds on a foundation of space, especially the ability to map exact numbers to linear space. This "mental number-line" is known to vary cross-culturally, but there is debate about the mechanisms responsible for its cultural elaboration. We investigated the role of co-speech gesture, a ubiquitous cultural activity, in stabilizing and entrenching the mental number-line within a community. Imitating culture-specific gestures systematically shaped gesturers' mental number-line. Moreover, gestures were used spontaneously to infer speakers' spatial understanding of number, and merely observing these gestures was sufficient to shape the observer's own mental number-line. These findings establish co-speech gesture as one mechanism for propagating and perpetuating the number-line.

Keywords: numerical cognition; SNARC; mental number-line; gestural contagion; gesture

Introduction

"[Space] provides a location for all things that come into being. […] [E]verything that exists must of necessity be somewhere, in some place and occupying some space." – Plato, *Timaeus*

From calculus to the complex plane, mathematics is rife with links between number and space. This is reflected in the human mind (Hubbard et al, 2005; Lakoff & Núñez, 2000; Winter, Marghetis, & Matlock, 2015). In many cultures, for instance, people can conceptualize exact numbers as locations along a horizontal path (e.g., Dehaene et al, 1993; Dehaene et al, 2008; Shaki, Fischer, & Pretrusic, 2009), known as a mental number-line (MNL). The MNL has been argued to contribute to diverse mathematical abilities, including the mental representation of number (Zorzi, Priftis, & Umiltà, 2002; Opfer, Thompson, & Furlong, 2010), arithmetic (Knops et al, 2009, Marghetis et al, 2014), and understanding complex concepts like imaginary numbers (Lakoff & Núñez, 2000).

The MNL figures prominently in debates about the origin of abstract concepts in the human mind, since there is evidence that it emerges from a mix of innate biases and cultural influences (e.g., Shaki et al, 2009; Núñez, Cooperrider, & Wassman, 2014; Rugani et al, 2015). For instance, human neonates associate approximate numerical magnitude with spatial length (de Hevia et al, 2014), an early disposition that may support the acquisition of more precise mappings between exact numbers and spatial locations (i.e. the MNL). These early dispositions are elaborated considerably by cultural experience, with cross-cultural variability in the MNL's orientation (Shaki et al, 2009), whether the number-space mapping is linear or logarithmic (Dehaene et al, 2008), and even whether the MNL exists at all (Núñez & Wassman, 2012). For instance, while Western adults typically exhibit a left-to-right MNL, Arabic-speaking Palestinians exhibit a right-to-left MNL (Shaki et al, 2009). Thus, beyond any innate biases, culture-specific aspects of the MNL propagate and stabilize within communities. This cultural elaboration requires explanation.

How this happens, however, is poorly understood. Language is one possible mechanism. Many languages, like English, place numbers in vertical space (e.g. "high [/low] number"). But language can't be the whole story. There are no known uses of horizontal spatial language or distinctively linear versus logarithmic language to refer to number. In neither English nor Arabic, for instance, are numbers described using the words for *left* and *right*. Other proposed mechanisms include writing direction (Shaki et al, 2009), finger-counting routines (Bender & Beller, 2012; Fischer, 2008), experience with technical artifacts (Siegler & Ramani, 2009), and formal education in topics like measurement (Dehaene et al, 2008). There is correlational evidence in favor of each proposed mechanism, but determining distinct causal contributions has proven challenging, in part because the mechanisms are correlated with one another and other cultural variables.

One cultural activity that has not been considered in this debate is *co-speech gesture*, communicative bodily movements produced spontaneously by speakers in all cultures (McNeill, 1992). This may be because—compared to more stable aspects of culture like artifacts or writing—gesture is transient and thus less likely to be noticed or, when noticed, harder to measure. But there are reasons to suspect that gesture might play a critical role in propagating and perpetuating the MNL. Both novices and experts gesture when talking about mathematics, and these gestures can reveal spatial intuitions that are absent from speech (Goldin-Meadow & Beilock, 2010; Marghetis & Núñez, 2013). Moreover, oriented, culture-specific associations between number and location emerge in children as young as four years old (Opfer et al, 2010; Hoffman et al, 2013), which means that cultural influences on the MNL begin before formal education, literacy, or mastery of artifacts like physical number-lines. But not before gesture starts to shape development (Rowe & Goldin-Meadow, 2009). Gestures about number, in particular, appear early: Two-year-old children and their caregivers produce numerical gestures spontaneously during play (Lee et al, 2014).

Critically, cross-cultural differences in the conceptualization of abstract concepts often covary with differences in gesture. Americans, for instance, think and talk about the future as ahead of them, and also point forward when talking about the future, while the Aymara people of the Andes place the future behind them in language, thought, and gesture (Núñez & Cooperrider, 2013). Numerical gestures similarly vary cross-culturally. The Oksapmin people of Papua New Guinea indicate exact numbers by pointing to locations along a body-based path that runs hand-to-hand (e.g., right thumb for one, left ear for sixteen), though individuals differ in the orientation of this system (i.e., left-to-right or right-to-left) (Saxe, 2014).

By contrast, when Americans talk about arithmetic, they gesture spontaneously in ways that reflect complementary spatial conceptualizations of number: as if numbers are locations along a horizontal *path* or, alternatively, as if numbers are *collections* of objects (Fig. 1; cf. Núñez & Marghetis, 2013). *Path* gestures represent numbers by pointing to locations along a horizontal axis in front of the speaker—smaller numbers to the left, larger numbers to the right (Fig. 1A). *Collection* gestures represent numbers as volumes in space, using either single-handed grasping gestures or, for larger numbers, two-handed gestures that delimit larger regions (Fig. 1B). These two kinds of gesture thus represent number in complementary ways.

Given the structural similarity between "Path" gestures and the MNL (e.g. both involve mapping numbers to locations along a path), these gestures may reflect gesturers' path-based understanding of number, that is, their MNL. Could these Path gestures not only reflect but actively shape the MNL? Along with other primates, humans imitate and learn from others' actions (Tomasello, 2014), but humans may be unique in acquiring gesture through social learning (Halina et al, 2013). Gesture systems are, among other things, repositories of culture-specific understandings of abstract concepts. The spread of gestures and their associated meanings may thus disseminate abstract concepts within human communities (Sperber, 1996), a process we call "gestural contagion." In several experiments, we asked whether gestural contagion contributes to propagating and perpetuating the MNL.

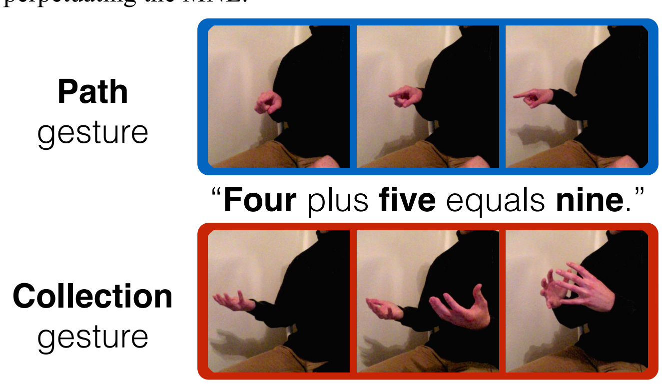

Fig. 1: *When Americans talk about number, they gesture spontaneously as if numbers are either locations along a path or collections of objects. We created pairs of videos (n=8) that had identical audio but different gestures: Path (top) or Collection (bottom). Gestures were modeled after naturally occurring co-speech numerical gestures. The same video stimuli were used in all experiments. Here, the speaker produces a gesture for each addend and their sum; boldface indicates lexical affiliates.*

Study 1: Reproducing gesture shapes the MNL

Since gestures, acquired through imitation, can shape the gesturer's own mental representations (Goldin-Meadow & Beilock, 2010), we first investigated whether imitating culture-specific gestures might shape one's own MNL. If observing and imitating numerical gestures shapes gesturers' own conceptualization of number, then participants should exhibit a more pronounced left-to-right MNL after reproducing left-to-right Path gestures.

Participants

Native-English-speaking adults from UC San Diego participated in exchange for partial course credit (n = 50, M_{age} = 21 years). In all three studies, we determined sample sizes in advance. For Study 1, sample size was determined on the basis of similar studies on the plasticity of the MNL (e.g. n = 44 in Fischer et al, 2010). All procedures were approved by UC San Diego's Institutional Review Board.

Materials

We created sixteen brief video clips, two for each of eight mathematical facts (e.g. 4 + 3 = 7; 8 – 6 = 2; 4 > 1). In each video clip, a man—depicted from the neck down—was heard stating a mathematical fact (e.g. "Four plus three equals seven.") and accompanied his speech with either *Path* or *Collection* gestures (Fig. 1A). To create the videos, we first audio-recorded the man stating the eight mathematical facts. Then, for each recorded fact, we made two video-recordings: one in which the man produced naturalistic Path gestures in time with the pre-recorded speech, and another in which he produced naturalistic Collection gestures. These two video-recordings were then combined with the pre-recorded audio to create eight pairs of video files. Paired videos thus had identical audio[1] but contrasted in co-speech gesture (i.e. Path vs. Collection), allowing us to control for any differences in speech.

Procedure[2]

In a between-subjects design, participants completed two tasks: an initial Gesture Imitation task in which they reproduced either Path or Collection gestures, followed by a standard Number Comparison task designed to measure associations between numbers and lateral space, i.e. the SNARC effect (Dehaene et al, 1993).

Gesture Imitation task: Participants viewed either Path or Collection video clips (see *Materials*, above) and reproduced the clips' speech and gesture. The type of gesture (*Path* vs. *Collection*) was manipulated between-

[1] To minimize incongruity between cross-spliced audio and video, the speaker's throat and mouth were kept outside the video frame.
[2] In all three studies, we report how we determined all sample sizes, exclusions, manipulations, and measures (Simmons et al, 2012).

subjects and assigned randomly. In each trial, the experimenter played a video clip once and then asked the participant to reproduce exactly the speech and gesture. Participants were given the opportunity to re-watch each video until they were able to reproduce both speech and gesture. Since our hypothesis was about the impact of the specific gestures in the videos, participants were reminded to reproduce everything that happened in the video whenever they made errors. One block consisted of viewing and reproducing all eight Path or Collection videos. Participants completed four blocks—always with the same type of gesture—for a total of thirty-two trials.

Number Comparison task: Participants judged whether positive integers (1 to 9, inclusive) were greater or less than 5, a replication of the classic SNARC paradigm (Dehaene et al, 1993). Each trial began with a fixation cross in the center of a computer monitor, replaced after 1000ms by an Arabic numeral between 1 and 9 (excluding 5). Participants had up to 3000ms to respond by pressing one of two buttons on a serial response box: the leftmost button with their left index finger or the rightmost button with their right index finger. Participants completed two blocks, each of which began with eight practice trials (one for each numeral) followed by eighty experimental trials (ten for each numeral); trial order was randomized within blocks. Critically, we manipulated, between blocks, the mapping between responses (*greater* vs. *less than 5*) and spatial location (*left* vs *right*). Thus, e.g., in response to numbers less than five, participants had to respond on the left in one block and on the right in the other. Block order was counterbalanced between subjects. If a participant had a canonical left-to-right mental number-line, therefore, they would be faster to categorize smaller numbers when responding on the left, and faster to categorize larger numbers on the right. We measured accuracy and reaction time.

Results

Two participants were removed for poor accuracy (< 80%). Accuracy was high among remaining participants (M = 94.8%, 95% CI [93.6, 96.1]). Before analyzing reaction times, we removed incorrect responses (5.2% of trials), followed by responses that were either faster than 275ms or slower than three standard deviations above the participant's condition mean (2.3% of trials).

Reaction times were analyzed in a 2x2x4 mixed-design ANOVA, with Gesture Type (*Path* vs. *Collection*) as a between-subjects factor, and Response (*left* vs. *right*) and Numerical Magnitude (*1-2, 3-4, 6-7,* or *8-9*) as within-subjects factors. Overall, participants exhibited a left-to-right MNL, as revealed by a two-way interaction between Response and Numerical Magnitude ($F_{(3,138)}$ = 7.4, p = .0001). This was modulated, as predicted, by the type of gesture they had reproduced ($F_{(3,138)}$ = 3.17, p = .026).

To quantify this effect, we calculated, for each participant and each number, the difference between mean left- and right-sided reaction times (dRT), and then regressed dRT against numerical magnitude. The magnitude of the regression slope ("SNARC coefficient," β) indicates the strength of the number-space association; the slope's sign indicates the association's orientation (negative slopes indicate a left-to-right MNL). Participants in both conditions showed evidence of a canonical left-to-right MNL (β_{path} = -17.5; $\beta_{collection}$ = -4.5; Fig. 2A), but, as predicted, the MNL was far more pronounced after observing and reproducing Path gestures (t_{46} = -1.8, p = .036, one-tailed; Fig. 2B).

In sum, imitating culture-specific gestures shaped gesturers' MNL. Gesturing as though numbers were locations along a path caused participants to conceptualize numbers accordingly.

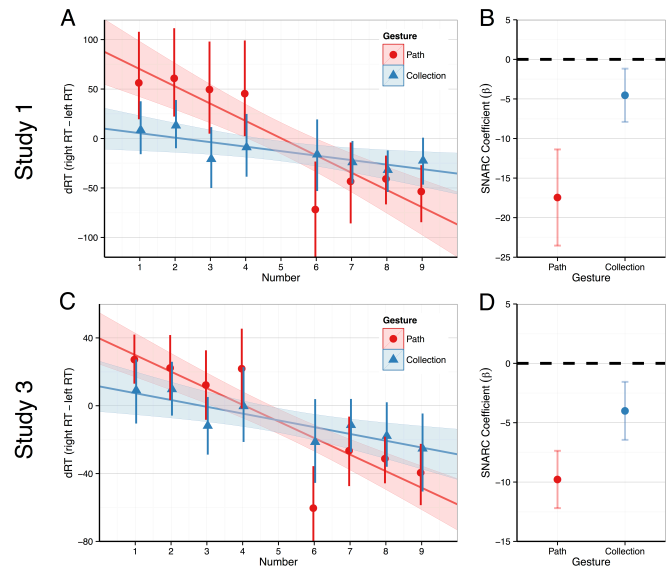

Fig. 2: Effect of gesture on the MNL, as indexed by the SNARC effect. (A, C) In both studies, there was evidence overall of a left-to-right MNL (i.e. negative regression coefficient), but this was significantly more pronounced for Path gestures. Error lines and shaded regions indicate bootstrapped 95% confidence intervals. (B, D) In both studies, participants' MNL, as indexed by SNARC regression coefficients (± SEM), was more pronounced in the Path gesture condition.

Study 2: Gesture shapes interpretation of gesturers' understanding

We next investigated whether merely *observing* gestures, rather than imitating them, could propagate spatial understandings of number within a community. Since humans excel at inferring conspecifics' intentional states (Tomasello, 2014), observers might use a speaker's gestures to discern their number understanding, thus becoming aware of spatial construals in circulation within the community. We tested this possibility in an online experiment.

Participants

Participants (n = 50), recruited from Amazon Mechanical Turk, were native-English speaking adults located in the USA and participated in exchange for payment. Sample size was determined on the basis of similar studies on gesture and comprehension (e.g. $n = 44$, Kelly et al, 2010).

Procedure

Participants began by viewing all eight video clips from Study 1, with gesture (*Path* vs. *Collection*) assigned randomly between-subjects. Without mentioning gesture, we then asked participants to describe the speaker's understanding of number. First, they were asked to describe, in a few sentences, the speaker's "understanding of number and arithmetic." Second, they were asked whether the speaker's understanding was best captured by "numbers are like locations along a path" or "numbers are like collections of objects." Lastly, as a manipulation check, participants were asked whether they had paid attention to the speaker's gestures (every participant responded at least "maybe a little") and were played two video clips and asked whether or not they recognized them (every participant was correct on either one or both of these clips). They finished by supplying demographic information (gender, age, ZIP code, education, primary occupation, languages spoken). No other measures were collected.

Results

To determine the "gist" of participants' descriptions, we used an unsupervised machine learning technique, Latent Dirichlet Allocation (LDA). On the basis of the words in a set of texts (in this case, participants' descriptions), LDA builds a generative model of latent topics discussed in the texts (Griffiths et al, 2007). Since participants were exposed to two ways of gesturing about number, we decided *a priori* to fit a model with two latent topics.

One of the latent topics extracted by the model was associated with terms like "part," "whole," and "together," and appeared to capture a *collection-based* understanding of number (e.g. "numbers as groups of things"). The other topic was associated with terms like "left" and "right," and appeared to capture a *path-based* understanding (e.g. "sees them going from left to right"). As a measure of the gist of participants' descriptions, we used the mean-centered posterior probability that each description dealt with the path-based (vs. collection-based) topic. A positive value of this measure thus indicates that the description was more path-related than average; a negative value indicates that the description was more collection-related than average.

Critically, even though gesture had not been mentioned in any instructions, the gist of participants' descriptions was shaped by the speaker's gesture (Fig. 3A). There was a significant effect of gesture on participants' interpretation of the gesturer's conceptualization ($p < .01$, Mann-Whitney). If the speaker used Path gestures, descriptions of his understanding were more path-based overall ($M = -0.12$) and most participants (74%) gave a *path*-based description; if he used Collection gestures, descriptions were more collection-based ($M = 0.20$) and most participants (58%) gave *collection*-based descriptions. Indeed, when we asked participants whether the speaker's conceptualization was best characterized in terms of "locations along a path" or "collections of objects," their responses were shaped by his gesture ($p < .001$, Fisher's exact; Fig. 3B), with most participants (71%) responding that he understood numbers as "locations along a path" if he had produced *Path* gestures ($p = .03$, binomial test), and most (80%) responding that he understood numbers as "collections of objects" if he had produced *Collection* gestures ($p = .01$).

Numerical gestures, therefore, were meaningful for naïve observers, who spontaneously relied on them to infer the speaker's spatial conceptualization of number.

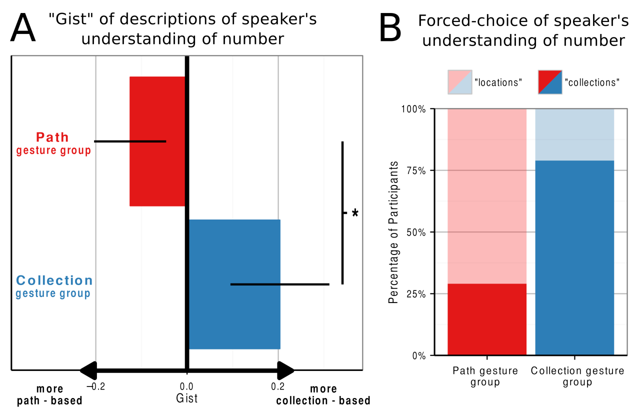

Fig. 3: *Gesture shaped observers' interpretation of speaker's conceptualization of number (Study 2). (A) Participants spontaneously incorporated information from the speaker's gesture into their descriptions of his conceptualization (p < .01). Positive values of gist indicate more collection-based descriptions; negative values, more path-based descriptions. Error lines indicate SEM. (B) When forced to decide whether the speaker conceptualized numbers as "locations along a path" or "collections of objects," most participants chose the conceptualization that aligned with his gesture (p < .001).*

Study 3: Gesture observation shapes observer's MNL

Intersubjective coordination of thinking is a cornerstone of human culture (Tomasello, 2014). Study 3 thus investigated whether merely observing gestures not only sways observers' inferences about the *speaker's* understanding (as found in Study 2) but also shapes observers' *own* MNL. As in Study 1, participants were exposed to prerecorded Path and Collection gestures, with one change: We directly manipulated whether participants reproduced the gestures actively or merely observed them passively.

Participants

Native-English-speaking adults from UCSD participated in exchange for partial course credit ($n = 122$, $M_{age} = 21$ years). An *a priori* power analysis found that a sample size of 116 participants would have sufficient power ($1\text{-}\beta > 0.95$) to replicate the effect from Study 1. We thus settled in advance on n = 124 or as close as possible by the end of the term.

Procedure

The design was identical to Study 1, with one exception: In the Gesture Imitation task, participants either had to reproduce speech and gesture both, as in Study 1, or had to reproduce speech alone, assigned randomly between subjects.[3]

Results

Four participants were removed for poor accuracy (< 80%). Accuracy was high among remaining participants (M = 94.3%, 95% CI [93.9, 94.6]). As in Study 1, before analyzing reaction times, we removed incorrect responses (5.7% of trials), followed by those either faster than 275ms or slower than three SDs above participants' condition mean (4.0%). Reaction times were analyzed in a mixed-design ANOVA, with Gesture Type (*Path* vs. *Collection*) and Gesture Reproduction (*Reproduce* vs. *Observe*) as between-subjects factors, and Response (*left* vs. *right*) and Numerical Magnitude (*1-2, 3-4, 6-7,* or *8-9*) as within-subjects factors.

There was a significant overall left-to-right MNL ($F_{(3,339)}$ = 12.5, p << 0.001), once again influenced by whether participants were exposed to Path or Collection gestures ($F_{(3,339)}$ = 2.8, p = .038). Critically, this was unaffected by whether participants had reproduced rather than merely observed the gestures (all Fs < 1.72, all Ps > 0.19).

Regression analyses, as in Study 1, confirmed the overall tendency of a left-to-right MNL in both gesture conditions (β_{path} = -10.0; $\beta_{collection}$ = -3.9; Fig. 2C), along with a significant impact of gesture, such that participants in the Path condition had a more pronounced left-to-right MNL than in the Collection condition (t_{117} = -1.8, p = .04, one-tailed; Fig. 2D).

Moreover, gesture had a significant influence on the MNL even when only passively observed ($F_{(3, 171)}$ = 2.8, p = .04). Thus, gestures had a significant impact on the MNL even when merely observed passively.

Finally, to confirm the causal influence of gesture across Studies 1 and 3, we constructed a linear mixed-effects model[4] of individual SNARC coefficients. The model confirmed the causal influence of gesture on the MNL (p = .016), unmodulated by whether gestures were reproduced or observed (P = .68; Table 1).

[3]Afterwards, participants completed a pilot study on arithmetic (e.g. 4 + 3) and bisection (e.g. bisection 3 and 7) problems. These data are not analyzed here. No other measures were collected.

[4]We used the maximal converging random effects structure: uncorrelated intercepts and slopes for both factors and their interaction. Models were fit using restricted maximum likelihood; we used Satterthwate's approximation to get p-values for parameter estimates. SNARC coefficients were standardized for each experiment to control for differences in sample populations.

Table 1. Influences on the MNL (Studies 1 and 3)

Predictor of SNARC effect	Coef.	*SEM*	*P*(>|*t*|)
Gesture (*Path* vs. *Collection*)	–0.372	0.15	.02
Reproduction (vs. *Observation*)	0.188	0.16	.24
Gesture x Reproduction	–0.134	0.32	.68
Intercept	0.000	0.07	.99
No. of observations (groups)	165 (2)		
Log-likelihood	–231.33		

Table 1. *Effect of gesture content on the MNL (indexed by SNARC effect) in Studies 1 and 3. There was evidence overall of a left-to-right mental number-line (i.e. negative regression slope), but this was significantly more pronounced after exposure to Path gestures.*

General Discussion

Previous research has found considerable cross-cultural variability in the mental number-line, often attributed to differences in writing practices, finger-counting, or formal education. Our findings suggest that co-speech gesture also plays a causal role in propagating and perpetuating the MNL. Imitating culture-specific numerical gestures impacted the gesturer's MNL; observing those gestures helped the observer infer the speaker's spatial understanding of number and influenced the observers' own MNL, even when unmediated by gesture imitation. In humans, therefore, action imitation and interpretation appear to propagate not just culture-specific behaviors, as previously established by work on social learning of action (Tomasello, 2014), but also culture-specific conceptualizations of abstract ideas (cf. Sperber, 1996).

By taking advantage of within-culture variability in the gestural representation of number (Fig. 1), we were able to experimentally manipulate one aspect of culture while controlling for others, such as literacy, language, or formal education. These other factors, however, may also shape the spatial conceptualization of number, with multiple mechanisms operating over disparate timescales to reproduce an interpersonally-shared MNL. Artifacts like graphs and practices like literacy, for instance, are enduring cultural influences that can stabilize the MNL on an historical timescale. The specific contribution of gesture may derive from its combination of flexibility and conventionality. Spatial-numerical associations, while stable at the population-level, are highly flexible within individuals (e.g., Fischer et al, 2010). Gesture may regiment individuals' flexible conceptualizations, aligning numerical intuitions within a community to maintain socially coordinated thinking. It remains to be seen whether gestural contagion could spread the MNL to communities that lack the concept entirely (Núñez et al, 2012) or reverse the MNL in communities where it already exists (Shaki et al, 2009; Fischer, 2008).

If non-human primates acquire complex behaviors but not gestures through social learning (Halina Rossano, & Tomasello, 2013), gestural contagion may be a uniquely human mechanism for cultural transmission, particularly of space-related domains. Cultures differ in how they talk and think about abstract concepts like time, social relations, and even space itself, and these culture-specific understandings are often expressed in gesture (Núñez & Cooperrider, 2013; Enfield, 2005; Levinson, 2003). Thus, differences in multimodal communication may not only reflect but actively drive cross-cultural differences in abstract thought, including but not limited to the MNL. Across a variety of conceptual domains, cultural knowledge may be propagated and entrenched through gestural contagion.

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