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The Correlations in Experience Principle: How Culture Shapes Concepts of Time and Number

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People use space to conceptualize abstract domains like time and number. This tendency may be a cognitive universal, but the specifics of people's implicit space–time and space–number associations vary across cultures. In Western cultures, both time and numbers are arranged in people's minds along an imaginary horizontal line, from left to right, but in other cultures the directions of the mental timeline (MTL) and mental number line (MNL) are reversed. How does culture shape our abstract concepts? Using time and number as a testbed, we propose and test a general principle, which we call the *CORrelations in Experience (CORE) principle*, according to which different aspects of experience should selectively affect different abstract concepts. Across 3 training experiments, the MTL was shaped by experiences that provide a correlation between space and time, whereas the MNL was shaped by experiences that provide a correlation between space and number. These findings reveal that the MTL and MNL have distinct experiential bases, supporting the CORE principle and challenging the widespread claim that both mappings are determined by a common set of cultural experiences (e.g., reading, writing, visual scanning). The CORE principle provides an account of how domains like time and number, universal fixtures of the natural world, can be conceptualized in culture-specific ways: People spatialize abstract domains in their minds according to the ways those domains are spatialized in their experience.

Keywords: metaphor, number, SNARC effect, spatial cognition, time

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From early in life, people associate time and number with space (de Hevia, Izard, Coubart, Spelke, & Streri, 2014; de Hevia, Veggiotti, Streri, & Bonn, 2017). This tendency may be universal, but by the time children are in preschool they begin to show space–time and space–number associations that differ across cultures (Shaki, Fischer, & Göbel, 2012; Tversky, Kugelmass, & Winter, 1991). How does culture shape our conceptions of time and number? For nearly three decades researchers have posited that the same experiences, in particular reading and writing, determine cross-cultural variation in both space–time and space–number associations (Bonato, Zorzi, & Umiltà, 2012; Patro, Nuerk, & Cress, 2016; Tversky et al., 1991). Yet, although this proposal is widely accepted, we argue that it is neither clearly motivated by theory nor well supported by data.

Here we provide evidence for an alternative proposal that specifies how different abstract conceptual domains, like time and number, are selectively shaped by different aspects of experience. We call this proposal the *CORrelations in Experience (CORE) principle*. According to CORE, abstract domains are spatialized in people's minds the way these domains are spatialized in the world.

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This simple principle allows us to predict a priori which kinds of experiences should—and should not—influence the spatial mapping of any abstract domain. Consistent with CORE, and contra previous proposals, we show that conceptions of time are selectively shaped by cultural practices that spatialize time, whereas conceptions of number are selectively shaped by practices that spatialize numbers.

Lateral Spatial Mappings of Temporal and Numerical Order

In Western cultures, people associate earlier events with the left side of space and later events with the right, forming an implicit mental timeline (MTL) that progresses from left to right. Likewise, Westerners associate smaller numbers with the left and larger numbers with the right, forming an implicit mental number line (MNL) that increases from left to right. These spatial mappings of time and number are evident in people's spontaneous gestures (Casasanto & Jasmin, 2012; Fischer, 2008; Shaki et al., 2012) and eye movements (Fischer, Castel, Dodd, & Pratt, 2003; Loetscher, Bockisch, & Brugger, 2008) across lateral space, and have been demonstrated in hundreds of experiments using reaction time (RT) tasks: People tend to respond faster to earlier events and smaller numbers using their left hand and to later events and larger numbers using their right hand (Bonato et al., 2012; Dehaene, Bossini, & Giraux, 1993; Wood, Willems, Nuerk, & Fischer, 2008)—at least in Western cultures. By contrast, people in some other cultures show the opposite set of associations, indexing MTLs or MNLs that progress in the opposite direction, from right to left (e.g., Fuhrman & Boroditsky, 2010; Shaki, Fischer, & Petrusic, 2009). In short, different cultures use space differently to conceptualize abstract domains like time and number.[1]

What aspects of culture determine the directions of the MTL and the MNL? On the basis of cross-cultural variation, many scholars have assumed that the directions of both the MTL and MNL depend on the direction in which people read and write text, or scan other visual materials. Yet, although this assumption is well supported for the MTL there is no clear evidence that these experiences influence the MNL. Even after decades of research, it has remained unclear *which experiences* influence which spatial mappings, and *why* (McCrink & de Hevia, 2018). The CORE principle addresses these questions.

Does Reading Experience Shape the MTL?

Does the direction of the MTL covary reliably across cultures with the direction of reading and writing? Yes. Whereas Westerners who write from left to right show MTLs that progress rightward (e.g., Spaniards: Santiago, Lupáñez, Pérez, & Funes, 2007; Canadians: Weger & Pratt, 2008), people from cultures where text is written from right to left typically show a corresponding reversal in the MTL (i.e., earlier events on the right, later events on the left; Arabic: Tversky et al., 1991; Hebrew: Fuhrman & Boroditsky, 2010; Ouellet, Santiago, Israeli, & Gabay, 2010; cf., Tversky et al., 1991), and people who cannot read or write show no reliable lateral MTL (Guida et al., 2018).

Beyond this clear correlation, training experiments have shown that reading experience can play a causal role in determining the direction of the MTL. Casasanto and Bottini (2014) randomly assigned Dutch speakers to read text in either normal orthography (from left to right) or mirror-reversed orthography (from right to left) while classifying events as either earlier or later in time. Participants who read normally were faster to classify earlier events with their left hand and later events with their right hand, reflecting the left-to-right MTL typical of Westerners. By contrast, those who read mirror-reversed text had the opposite pattern of RTs, showing a right-to-left MTL like that of Arabic speakers. Similarly, when participants read vertical text that progressed upward or downward, their MTLs changed orientation and direction, accordingly. Varying the direction of written text changed the direction of the MTL while all other cultural and linguistic factors were held constant. Beyond the laboratory, multiple kinds of culture-specific experience are likely to covary with reading direction (e.g., the horizontal arrangement of time on calendars and graphs), but these training data show that reading experience, alone, is sufficient to determine the direction of the MTL.

In sum, both correlational data (from cross-cultural experiments) and true experimental data (from laboratory interventions) support the claim that reading and writing are among the culture-specific experiences that can shape the MTL.

Does Reading Experience Shape the MNL?

Does the direction of the MNL covary reliably across cultures with the direction of reading and writing? No. Westerners tend to show MNLs that increase from left to right, consistent with the direction in which they read and write (e.g., British: Maier, Goebel, & Shaki, 2015; French: Dehaene et al., 1993; Scottish: Fischer, 2008; Canadian: Shaki et al., 2009). However, close examination of the evidence reveals no consistent support for the claim that the direction of the MNL follows the direction of written text in cultures that read from right to left.

In their seminal study establishing the Spatial-Numerical Association of Response Codes (SNARC) effect, Dehaene and colleagues (1993) found that French participants responded faster to small numbers with the left hand and large numbers with the right. However, this same study found "no evidence" of a reversed SNARC effect in Iranians, despite the right-to-left orthography in their culture (Dehaene et al., 1993, p. 385; see the online supplemental materials for a detailed discussion of this study, which is commonly misinterpreted as providing

[1] Findings in human infants and nonhuman animals have been interpreted as evidence of an innate predisposition to associate smaller numbers with the left side of space and larger numbers with the right (de Hevia et al., 2017; Rugani, Vallortigara, & Regolin, 2015). However, these findings are subject to alternative explanations, and some results may not reflect space–number associations at all (Vallortigara, 2018). Further research is needed to clarify how the initial evidence for left-to-right mappings of number in infants and nonhuman animals should be interpreted, and to determine the developmental and evolutionary starting points for our spatial representations of time and number. Even if these representations start out universal, however, they end up varying across cultures. The CORE principle can explain how this diversity of thought arises from the diversity of human experience.

evidence that the MNL depends on writing direction).[2] Likewise, Hebrew-speaking Israelis, who also write text from right to left, do not show reversed SNARC effects. Although some studies have interpreted null SNARC effects among Israelis as the result of reading habits (e.g., Shaki & Fischer, 2012; Shaki et al., 2009), the only significant SNARC results in Israelis have shown standard left-to-right MNLs like those of Westerners (Feldman, Oscar-Strom, Tzelgov, & Berger, 2019; Fischer & Shaki, 2016; Shaki & Gevers, 2011; Zohar-Shai, Tzelgov, Karni, & Rubinsten, 2017).

Another study (Zebian, 2005) has often been cited as evidence that reading direction predicts the direction of the MNL, but the results are uninformative for at least two reasons. First, although Zebian found a reversed SNARC effect in Arabic speakers, this right-to-left SNARC effect was *weaker* in a group of Arabic monolinguals than in Arabic-English bilinguals who had daily exposure to Western writing systems, contrary to predictions based on reading experience. Second, Zebian found no SNARC effect when testing illiterate participants; this null effect has been interpreted as support for the importance of reading experience in shaping the MNL. Yet, in addition to the inherent difficulty of interpreting null results, Zebian found the same null SNARC effect in English monolinguals—contrary to predictions, and to dozens of other findings in Westerners. Therefore, these data do not support any clear inferences about the relationship between reading experience and the MNL (see Shaki et al., 2009 for a similar critique of these data).

The clearest demonstration to date of a right-to-left SNARC effect was found among Arabic-speaking Palestinians (Shaki et al., 2009), consistent with the direction of Arabic text. However, this reversed SNARC effect can be explained on the basis of a cultural practice that *correlates* with reading and writing. In addition to writing text from right to left, these Palestinian participants also habitually wrote *numbers* from right to left, using the same Arabic-Indic numerals with which their SNARC effects were tested. Therefore, this reversed SNARC effect may reflect the direction of written numbers and not the direction of reading and writing text per se (for similar findings, see Maier et al., 2015; Shaki, Petrusic, & Leth-Steensen, 2012). In sum, although the body of studies reviewed here is often cited as (correlational) evidence that reading direction shapes the MNL, it provides no clear support for this claim.

Beyond these correlational data, is there any evidence that reading experience plays a causal role in directing the MNL? No. In one set of experiments, Hebrew-Russian bilinguals showed weakened SNARC effects after brief exposure to Hebrew words (Fischer, Shaki, & Cruise, 2009; Shaki & Fischer, 2008). These findings are often interpreted as evidence for a causal role of reading experience in determining the direction of the MNL, but they are purely correlational for the same reason that all cross-cultural comparisons are correlational. Although participants were assigned to read in one language or the other during the experiment, Hebrew and Russian differ not only in the direction of their orthography but also in myriad other ways that languages and cultures can differ. Presenting stimuli to participants in Hebrew or Russian likely activated a variety of culture-specific associations, not restricted to reading or writing experience, any of which might have affected their subsequent spatialization of numbers (see also Hung, Hung, Tzeng, & Wu, 2008). Indeed, SNARC effects differed between Hebrew and Russian stimuli no matter whether the stimuli were presented visually or auditorily. Culture-specific MNLs were found even in the *absence* of written text (Fischer et al., 2009; cf. Shaki & Fischer, 2008), suggesting that some aspect of linguistic or cultural experience other than the direction of written text may have been responsible for the Russian-Hebrew differences. To test for a causal role of reading direction on the MNL, it is necessary to manipulate participants' exposure to orthography while holding all other linguistic and cultural factors constant.

To date, there has only been one direct test for a causal role of reading experience in directing the MNL. In their seminal study, Dehaene and colleagues had French participants respond to number words that were presented in either normal or mirror-reversed orthography. In this design, any difference in the SNARC effect across conditions could only be attributed to the direction of orthography (and not to other aspects of language or culture). Contrary to the authors' predictions, however, orthography had no effect on the strength or direction of the SNARC; Participants showed normal SNARC effects in both conditions, which did not differ statistically (Dehaene et al., 1993: Experiment 8). In spite of this null result, the researchers concluded that "[t]he particular direction of the spatial-numerical association seems to be determined by the direction of writing" (Dehaene et al., 1993, p. 394). This claim, which we call the *reading/writing hypothesis*, has influenced a generation of researchers, who have concluded that reading/writing plays a "fundamental" (Rugani & de Hevia, 2017), "crucial" (Bonato et al., 2012, p. 2270), and "pronounced" (Patro et al., 2016, p. 4) role in determining the direction of the MNL. According to one review of more than two decades of MNL research, "the effect of reading/writing direction in affecting the spatial-numerical association has been shown unambiguously" (Rugani & de Hevia, 2017, p. 364), indicating the confidence that many researchers have in the reading/writing hypothesis—despite the evidence against the hypothesis detailed here.

In summary, whereas the claim that reading experience can shape the MTL is well supported by both correlational and causal evidence, there is no such support for the claim that reading experience can shape the MNL. On the contrary, multiple MNL studies fail to support the reading/writing hypothesis, producing either null results (e.g., Dehaene et al., 1993, Expt. 8; Shaki et al., 2009) or results that directly contradict the hypothesis (e.g., Dehaene et al., 1993, Expt. 7; Fischer & Shaki, 2016; Zohar-Shai et al., 2017). Despite this mismatch between the hypothesis and the available data, the reading/writing hypothesis (in one form or another) has remained widely accepted.

The reading/writing hypothesis has been modified over the past two decades in light of new findings. Several studies have found

[2] The average SNARC slope reversed only when Deheane and colleagues extrapolated beyond the data, in an attempt to infer the SNARC effects of participants before they emigrated from Iran (see Fischer, Mills, & Shaki, 2010). In exploratory, post hoc analyses, the authors reported a correlation between participants' SNARC effects and the number of years they had lived in France, but this reported effect (p = .05, one-tailed), does not approach statistical significance with appropriate correction for multiple comparisons (see the online supplemental materials for a detailed critique).

culture-specific MNLs in children who cannot yet read or write, some as young as 3 years old (Hoffmann, Hornung, Martin, & Schiltz, 2013; Opfer & Thompson, 2006; Opfer, Thompson, & Furlong, 2010; Shaki & Fischer, 2012). To accommodate such findings, some researchers have attributed the direction of the MNL not only to reading and writing but more generally to "spatially directional scanning of visual materials" (Shaki & Fischer, 2008, p. 596; see also Fischer, 2012; Patro, Fischer, Nuerk, & Cress, 2016; Zebian, 2005), turning the reading/writing hypothesis into a *reading/writing/scanning hypothesis*.

Several versions of the reading/writing/scanning hypothesis have been proposed, some expanding the set of experiences that could shape the MNL to include "all experienced actions and events oriented in space" (Patro et al., 2016, p. 4; see also Göbel, Shaki, & Fischer, 2011). Abstracting away from their differences, all versions of the reading/writing/scanning hypothesis state or imply that the direction of the MNL is determined by "experiencing spatially organized sequences of movement" (Patro et al., 2016, p. 3) with the eyes or other parts of the body, that these spatially directed activities "lead to cross-cultural differences in the spatial representation of numbers" (Göbel et al., 2011, p. 560), and that "reading is one such activity" (Fischer, Mills, & Shaki, 2010, p. 335).

Rather than rejecting the role of reading and writing in shaping the MNL, the reading/writing/scanning hypothesis proposes that other experiences are *complementary* to reading and writing. Researchers have suggested that "reading direction is not the *only* factor influencing the SNARC" (Fischer et al., 2010, p. 335, italics added), that the experiences affecting the MNL "are not constrained to reading" (Patro et al., 2016 p. 4), and that reading/writing experience plays a "crucial—although not exclusive—role" in shaping the MNL (Bonato et al., 2012, p. 2270; see also Rugani & de Hevia, 2017). Importantly, the reading/writing/scanning hypothesis entails the reading/writing hypothesis. Therefore, all versions of the reading/writing/scanning hypothesis are challenged by the studies reviewed above that fail to support— or directly contradict—the reading/writing hypothesis.

Synthesizing Previous Proposals About the Directions of the MTL and MNL

Reading, writing, and other "spatially oriented activities" (Patro et al., 2016, p. 4) have been proposed to determine the directions of both the MTL and MNL. This proposal is implied whenever the direction of the MNL is attributed to reading, writing, and/or scanning, given that the MTL is shaped by these same experiences. Beyond this implication, some authors have claimed explicitly that the MTL and MNL depend on the same experiences. For example, Bonato and colleagues (2012) posit an important "role of writing direction in the orientation of *both mental lines*" (p. 2259, italics added). Likewise, Göbel (2018) says that "there is evidence that the culturally predominant reading direction modulates the association *not only between number and space but also between time and space*" (p. 232, italics added). Elsewhere, authors have suggested that one of these mental lines depends on the other. Göbel, McCrink, Fischer, and Shaki (2018), for example, discuss "aspects of reading observation [that] contribute significantly toward the orientation of *space–time, and thus space–number, mappings*" (p. 63, italics added).

In sum, the predominant accounts of the MTL and MNL entail the following conclusions: (a) Reading and writing experience shape both the MTL and the MNL, either because these specific activities play a "crucial" role in determining their directions (Bonato et al., 2012, p. 2270), or because reading and writing are examples of "spatially organized sequences of movement" (Patro et al., 2016, p. 3); (b) More broadly, the directions of the MTL and MNL should depend on the same set of culture-specific experiences either directly, because the same experiences shape both mental lines, or indirectly because one mental line depends on the other; (c) Therefore, any experience that shapes the MTL should shape the MNL, similarly. The studies we report here challenge all three of these conclusions.

Different Mappings Depend on Different Experiences: The CORE Principle

Both the MTL and MNL can be considered *mental metaphors*: point-to-point mappings between analog continuums in two different conceptual domains. In a mental metaphor, the *source domain* (e.g., space) serves as a scaffold for representing the *target domain* (e.g., time or number), which is typically more abstract (Casasanto, 2010; Lakoff & Johnson, 1980). In the case of the MTL and MNL, the source domain for both mappings is lateral space, and the target domains are time and number, respectively. In principle, a given target domain can be mapped onto space in one of several ways (as evidenced by the cross-cultural differences in the directions of the MTL and the MNL). What determines which space–time and space–number mappings people tend to use?

Here we argue that the way a source and target domain are mapped in the mind is determined by the way those domains are correlated in experience. In other words, metaphorical mappings in the mind reflect source-target correlations in the world: This is the CORrelations in Experience (CORE) principle. CORE makes clear predictions about which aspects of experience should shape a given mental metaphor—and which aspects of experience should not. Specifically, according to CORE, the MTL should be shaped selectively by experiences that provide a correlation between space and time, whereas the MNL should be shaped selectively by experiences that provide a correlation between space and numbers.

The idea that mental metaphors depend on correlations in experience is one of the foundational assumptions of Lakoff and Johnson's (1980, 1999) *conceptual metaphor theory*. CORE builds on Lakoff and Johnson's proposal, but also departs from it in several critical ways. According to Lakoff & Johnson, source-target mappings: (a) should be universal, at least for source and target domains that are experienced universally like space, time, and number; (b) should be acquired early in childhood on the basis of information in the natural world; (c) should be "fixed conceptual mappings," implemented in "permanent neural connections" (Lakoff & Johnson, 1999, p. 149; for discussion see Casasanto, 2017a). Yet, like other mental metaphors that have been documented in the 21st century, the MTL and MNL contradict all of these assumptions (for a review see Casasanto, 2017b). The CORE principle is a key component of a broader theory of metaphorical mental representation, *hierarchical mental metaphors theory* (HMMT; Casasanto, 2017a; Casasanto & Bottini, 2014; see General Discussion), that seeks to explain why source-target mappings can: (a) vary across individuals and groups even for universally experienced domains like space, time, and number; (b) emerge late in cognitive development on the basis of linguistic or cultural conventions; (c) change flexibly, throughout the life span, while remaining fundamental to the mental representation of abstract concepts.

What experiences should cause the MTL and MNL to vary across cultures, according to CORE, and are reading and writing among these experiences? To predict whether reading/writing experience should influence the direction of the MTL, or the MNL, we consider whether reading/writing experience provides a correlation between space and time, and between space and numbers. Does the experience of reading text provide a space–time correlation? Yes, when reading a line of English text, the reader's gaze starts on the left side of the page at an earlier time and ends on the right side of the page at a later time. This correlation between space and time is an unavoidable feature of reading and is reinforced on every line of text: Each new fixation occurs later in time and farther to the right in space. The opposite relationship holds in reading Arabic or Hebrew text: Each new fixation occurs later in time and farther to the left in space (Casasanto & Bottini, 2014).

By contrast, the act of reading text provides no clear correlation between space and numbers. Moving rightward across the page corresponds inevitably to progress through a series of points in time, but not through a series of numbers, unless the text includes written numerals or number words.[3] In principle, people could silently count words as they read; however, mentally representing exact numbers relies on verbal resources, and is highly susceptible to concurrent verbal interference (e.g., Frank, Fedorenko, Lai, Saxe, & Gibson, 2012). Therefore, it is unlikely that simply reading (non-numerical) text causes people to automatically activate mental representations of numbers covertly.

Like reading, visual scanning of text by preliterate children (e.g., when following an adult reader's finger across a page) provides an inevitable correlation between space and time, but not between space and numbers. Therefore, on the basis of the CORE principle, reading and scanning experience should shape the MTL but should *not* shape the MNL. Rather, the MTL and MNL should have distinct experiential determinants: Whereas the MTL should be shaped by aspects of experience that spatialize time, the MNL should be shaped by aspects of experience that spatialize number.[4]

Here we tested this proposal in three experiments. In Experiment 1, we tested the effects of reading experience (which provides a correlation between space and time) on the MTL and MNL by training participants to read English text presented either normally or mirror-reversed. Whereas the reading/writing/scanning hypothesis predicts that reading experience should affect the directions of both the MTL and MNL, CORE predicts that reading should only affect the MTL. In Experiment 2, we tested whether finger counting experience (which provides a correlation between space and number) can influence the MNL by training participants to count on their fingers in one direction or the other. Finally, in Experiment 3, we used a novel finger-counting protocol to test whether a single experience can have different effects on the MTL and MNL, by independently varying space–time and space–number correlations. Whereas the reading/writing/scanning hypothesis predicts that this finger counting training should have similar effects on the MTL and MNL, CORE predicts *opposite effects* on the MTL and MNL. Specifically, the direction of the MTL should follow the space–time correlations that participants experience, whereas the direction of the MNL should follow the space–number correlations that they experience.

Experiment 1: Can Reading Experience Shape the MTL and MNL?

Experiment 1 tested the effects of reading experience on the direction of the MTL and MNL by randomly assigning US participants to read either normal or mirror-reversed English text during a training phase. After reading training, we assessed the strength and direction of participants' MTL and MNL as indexed by their RTs on matched space–time and space–number congruity tasks. If reading direction can play a causal role in determining the direction of both the MTL and the MNL, then participants should show normal space–time and space–number congruity effects after reading normal text, and reduced (or reversed) effects after reading mirror-reversed text, for both time and number. This outcome would support the reading/writing hypothesis and its extensions, and would challenge CORE. Alternatively, if the MTL is selectively shaped by experiences that spatialize time, whereas the MNL is selectively shaped by experiences that spatialize number, then mirror-reversed reading—which necessarily spatializes time but not number—should reduce (or reverse) the space–time congruity effect but should not change the space–number congruity effect. This outcome would support the hypothesis that the directions of the MTL and MNL are determined by different experiences, according to the source-target correlations those experiences provide (i.e., the CORE principle).

[3] Although reading text in general does not provide a correlation between space and numbers, reading text that includes numbers can. For example, the multi-digit numbers that readers encounter have a peculiar property; according to the first-digit law (Benford, 1938), smaller numbers appear more often on the left side (e.g. in the tens place) and larger number appear more often on the right (e.g. in the ones place). Even single-digit numbers may be spatialized systematically in text; because people tend to list numbers in increasing order (e.g. "7 to 10 business days"; "3 or 4 pages"), smaller numbers may tend to appear to the left of larger numbers. To the extent that such patterns cause numbers to be systematically spatialized in text, CORE predicts that reading numbers in text should affect the MNL. However, this effect is likely to be small because (a) number symbols constitute a small proportion of all written text, and (b) the correlation between numbers and space in ordinary text is likely to be weak (e.g., because the left-right position of numbers in text depends on line breaks). By contrast, the correlation between time and space applies to every line of text, regardless of its content.

[4] The MTL is a mapping between spatial position and temporal order, and the MNL is a mapping between spatial position and numerical order; these are *metathetic* aspects of space, time, and number; meaning that people experience *qualitative* variation but not quantitative variation in them (Stevens, 1957). The relationship between *prothetic* (i.e., quantitative) aspects of space, time, and number is the subject of a large literature, but it is only distantly relevant to the present studies, as we discuss in the General Discussion (in the section titled Can the Results Be Explained by a "Generalized Magnitude System?").

Method

All studies were approved by the by the Social Sciences Institutional Review Board of the University of Chicago, and all participants gave written informed consent.

Participants. Sixty-four right-handed native English speakers from the University of Chicago community participated for payment or course credit. The sample size was determined prior to the start of data collection on the basis of our previous experiments testing the effects of orthography on the MTL (Casasanto & Bottini, 2010).[5] Half of the participants were randomly assigned to the standard (rightward) reading condition ($n = 32$), and the other half to the mirror-reversed (leftward) reading condition ($n = 32$).

Materials and procedure. Participants performed a two-part experiment in which a training phase was followed by a test phase.

Training phase. In the training phase, participants read a passage silently in either standard or mirror-reversed orthography (see Figure 1, left panel). They were seated in front of a 24-in. Apple iMac computer (with the keyboard removed, to ensure that the left-to-right number line in the top row of keys was not visible to participants). They were told that they would be asked some comprehension questions after reading. Text appeared in black capital letters on a white background and spanned the width of the screen. The text, which was excerpted from *Zen and the Art of Motorcycle Maintenance* (Pirsig, 1974), consisted of 2,964 words and spanned 25 pages. After reading each page, participants pressed the central key on a button box to advance to the next page. On average, reading training lasted about 12 min in the standard condition and 36 min in the reversed condition and was limited to 45 min by the experimenter. After reading, participants responded to five comprehension questions by selecting one of two answers. These comprehension questions were not scored; this filler served to encourage attentive reading. Throughout training, all stimuli (including instructions, questions, and answers) were presented in capital letters in either standard or mirror-reversed orthography, according to training condition.

Test phase. The test phase immediately followed the training phase and consisted of three tasks, one testing the MTL (month task) and two testing the MNL (digit task and number word task). These three tasks were modeled on the classic tests of the SNARC effect and were matched in the construction of their stimuli (i.e., number of levels), instructions, and responses.

In the month task, three-letter abbreviations for the months of the year (February through October except June) appeared on the screen one at a time. Participants classified each month as either "earlier" or "later" than June in the calendar year by pressing one of two response keys (see Gevers, Reynvoet, & Fias, 2003). In one block of trials, participants used the left-hand key for months that were earlier and the right-hand key for months that were later. This response mapping was reversed in the other block of trials and block order was counterbalanced across participants. Participants used their left hand to press the left-hand key and used their right hand to press the right-hand key, in all experiments.

In the two number tasks (digits and number words), participants classified numbers (1–9 except 5) as either "greater" or "less" than five. For one block, they used the left-hand key for small numbers and the right-hand key for large numbers. In the other block, this response-mapping was reversed and block order was counterbalanced across participants. In the digit task, numbers were presented as Arabic numerals; in the number word task, they were presented as English number words. The digit and number word tasks are both established tests of the SNARC effect (see Fischer & Shaki, 2014, for review). By including both of these number tasks, we had two opportunities to detect any effects of reading training on the MNL. We used a "magnitude" variant of the SNARC task rather than the "parity" variant because magnitude judgments (greater vs. lesser) are more closely analogous to our temporal judgments (earlier vs. later) than are parity judgments (odd vs. even).

The order of month and number tasks was counterbalanced across participants such that the month task was first for half of participants and the number tasks were first for the other half of participants. Within the number tasks, the order of the digit and number word tasks was counterbalanced across participants.

In each block of each task, the eight unique stimuli appeared in random order eight times, composing 128 trials per task. At the beginning of each block, the experimenter asked participants to raise the hand corresponding to each of the responses to ensure they understood the response mapping. Each trial began with 500 ms of an empty black screen followed by a fixation cross whose duration varied uniformly between 500 and 1,000 ms. Throughout testing, all instructions and stimuli were presented on a black screen in white capital letters in either standard or mirror-reversed orthography, according to training condition. Participants were instructed to respond "as quickly and accurately as possible."

After testing, participants were debriefed to determine whether they were aware of the experimental hypotheses, and then completed a language history questionnaire and the Edinburgh Handedness Inventory (EHI; Oldfield, 1971).

Results

The raw data and analysis scripts for Experiment 1 are available in an OSF archive at https://osf.io/834dv/.

Exclusions. Three subjects who failed to follow instructions and one who guessed the purpose of the training were replaced.

Accuracy. Overall, accuracy was above 96%. According to repeated-measures binomial logistic regressions with random slopes and intercepts for subjects, the error rate did not differ significantly across reading conditions (standard = 3.20% ±0.16 *SEM*; reversed = 4.16% ±0.18 *SEM*; $\chi^2(1) = 2.10$, $p = .15$) or tasks (digits = 3.64% ±.21 *SEM*; number words = 3.28% ±.20 *SEM*; months = 4.11% ±.22 *SEM*; $\chi^2(1) = 5.41$, $p = .07$). Inaccurate trials (3.68% ±0.12 *SEM*) were excluded from the RT analyses.

RT analyses. To evaluate space–time and space–number congruity effects, months were coded for ordinal position in the calendar year. For all congruity effects, we used the lme4 package (Bates, Maechler, Bolker, & Walker, 2015) in R (R Core Team, 2017) to conduct linear mixed effects regression (lmer) models on RTs with response hand and ordinal position (of months or numbers) as predictors and with random slopes and intercepts for subjects. Space–time and space–number congruity effects were

[5] Although the efficacy of post hoc power analyses has been questioned (e.g. Hoenig & Heisey, 2001), in response to a reviewer's request we calculated the power for our main analyses post hoc. Across the three experiments, all tests showed power above 80%.

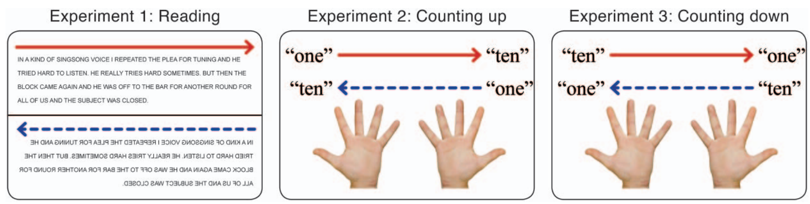

Figure 1. Training procedures for the three experiments. In Experiment 1 (left), participants read an English text in either standard orthography (solid red line) or mirror-reversed orthography (dashed blue line). In Experiment 2 (center), participants counted up to 10 either rightward (solid red line) or leftward (dashed blue line). In Experiment 3 (right), participants either counted down-to-the-right (solid red line) or down-to-the-left (dashed blue line). See the online article for the color version of this figure.

indexed by a significant interaction between response hand and ordinal position.[6] The effect of training condition on these congruity effects was indexed by a significant three-way interaction between response hand, ordinal position, and training condition. For each model, we first used a Box Cox test to determine how best to transform the data to approximate a normal distribution of residuals (Osborne, 2010).

To remove outliers, we intended to only exclude RTs more than 2.5 standard deviations (*SD*s) from subject means, following Casasanto and Bottini (2014). Unexpectedly, however, a small number of RTs were extremely long (exceeding 10 s, more than 10 times longer than the mean RT). To remove this small but influential subset of very slow RTs, we excluded all accurate trials slower than 2,000 ms (4.78%), and then performed outlier removal as planned (i.e., < 2.5 *SD*s).

Space–time associations. RTs greater than 2.5 standard deviations from subject means were removed (3.28%), following Shaki and Fischer (2008). RTs were then log transformed to approximate a normal distribution of residuals. In the standard reading condition, participants showed a significant standard space–time congruity effect in which they associated earlier months with the left and later months with the right, $\chi^2(1) = 20.63$, $p = .00006$ (slope $= -15.36$ ms/position ± 2.52 *SEM*). The space–time congruity effect in the reversed reading condition trended in the same direction but was only marginally significant, $\chi^2(1) = 2.62$, $p = .11$ (slope $= -7.91$ ms/position ± 2.74 *SEM*). Of primary interest, the space–time congruity effect was significantly weaker in the reversed reading condition than in the standard reading condition, $\chi^2(1) = 5.83$, $p = .02$ (Figure 2, left). Reading direction reliably changed the MTL, as predicted by the CORE principle.

Space–number associations. The digit task and number word task were first analyzed separately, and then their data were combined and analyzed together. This stepwise approach maximized the chances of detecting an effect of reading training on the MNL (a result that would support the reading/writing/scanning hypothesis and contradict CORE).

Digit task. RTs greater than 2.5 standard deviations from subject means were removed (4.20% of accurate responses). RTs were then transformed using an inverse square-root transformation to approximate a normal distribution of residuals. In the standard reading condition, participants showed a significant space–number congruity effect (SNARC effect), $\chi^2(1 = 5.68$, $p = .02$, in which they associated small numbers with the left and large numbers with the right (slope $= -7.61$ ms/position ± 1.92 *SEM*). Participants in the reversed reading condition also showed a significant standard SNARC effect, $\chi^2(1) = 12.06$, $p = .0005$ (slope $= -9.71$ ms/position ± 1.89 *SEM*). Of primary interest, the difference in the SNARC effects across reading conditions did not approach significance, $\chi^2(1) = .01$, $p = .91$.

Number word task. RTs greater than 2.5 standard deviations from subject means were removed (3.77% of accurate responses). RTs were then square-root transformed to approximate a normal distribution of residuals. In the standard reading condition, participants showed a significant standard SNARC effect, $\chi^2(1) = 4.45$, $p = .04$ (slope $= -6.03$ ms/position ± 1.66 *SEM*). Participants also showed a significant standard SNARC effect in the reversed reading condition, $\chi^2(1) = 6.44$, $p = .01$ (slope $= -3.18$ ms/position ± 1.85 *SEM*). Again, the difference in the SNARC effects across reading conditions did not approach significance, $\chi^2(1) = .90$, $p = .34$.

Comparison of number tasks. To compare the effect of reading condition between the digit task and the number word task, we conducted an lmer model on log-transformed RTs with position, response hand, reading condition, and task (digits vs. number words) as predictors and with random slopes and intercepts for subjects. The effect of reading condition on the SNARC effect did not differ between the two number tasks, $\chi^2(1) = .20$, $p = .65$. We therefore combined the RT data from the digit task and the number word task, doubling our item-wise power to detect an effect of reading direction on the MNL (a result that would support the reading/writing/scanning hypothesis and contradict CORE).

Number tasks combined. In the standard reading condition, participants showed a significant SNARC effect, $\chi^2(1) = 6.67$,

[6] As a simple measure of effect size and for comparison with other findings, we also report and plot the SNARC effect in each task as a regression slope, following Fias (1996), regressing untransformed dRT values (dRT = right-hand—left-hand RT) for each number or month over its ordinal position. Although these slopes can also be used for inferential statistics, using them here would be inappropriate for several reasons. Baayen, Davidson, and Bates (2008) show that this by-participant regression approach inflates Type 1 error rates. Furthermore, because Fias's method collapses over large amounts of data (here, a 128:1 compression) it is not suitable for testing the higher-order (three-way and four-way) interactions on which our experimental questions depend.

To be maximally conservative, we used the exact same two-way and three-way models to evaluate the effects in all experiments. All two-way interactions were evaluated using a model with maximal random-effect structure. All three-way (and higher-order) interactions were evaluated using the most complete random-effect structure that would allow all models to converge. The detailed structure of our mixed effects models is explicit in the analysis scripts in our OSF archive: https://osf.io/92jvf/.

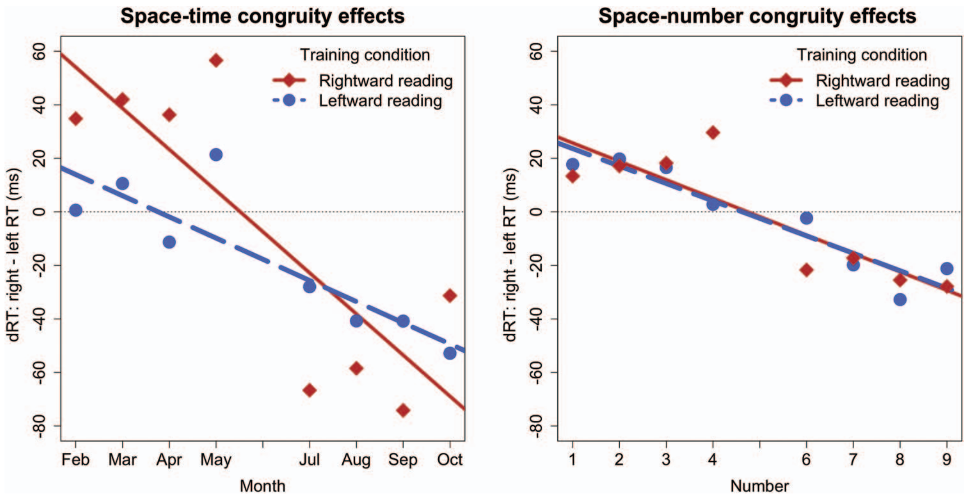

Figure 2. Results of Experiment 1. Left: The space–time congruity effects differed across reading conditions. Right: The space–number congruity effects did not differ across reading conditions; both conditions showed a standard SNARC effect. See the online article for the color version of this figure.

p = .01 (slope = −6.88 ms/digit ±1.40 *SEM*). Participants in the reversed reading condition also showed a significant standard SNARC effect, $\chi^2(1) = 6.28$, $p = .01$ (slope = −6.52 ms/position ±1.41 *SEM*). Of primary interest, the SNARC effects did not differ across reading conditions, $\chi^2(1) = .06$, $p = .80$ (Figure 2, right). Reading direction had no effect on the direction of the MNL, even when the data from the number tasks were combined.

Comparison of space–time and space–number effects. To compare the effect of reading direction on the space–time and space–number associations of our participants, we conducted an lmer model on log-transformed RTs with position, response hand, reading condition, and task (months vs. numbers) as predictors, with random slopes and intercepts for subjects. Reading condition had a reliably stronger effect on the space–time congruity effect than on the space–number congruity effect, $\chi^2(1) = 4.78$, $p = .03$, confirming that reading experience had different effects on the MTL and the MNL.

Discussion

Experiment 1 compared the effects of reading direction on the MTL and MNL in the same group of participants. After reading normal English text, participants showed the space–time and space–number associations typical of Westerners. After reading mirror-reversed text (from right to left), participants' space–time associations were significantly weakened[7] but their space–number associations were unchanged. These results support the claim that reading direction can influence the direction of the MTL (conceptually replicating the results of Casasanto & Bottini, 2014), but challenge the widespread claim that reading direction influences the MNL. This pattern supports the CORE principle and contradicts the reading/writing hypothesis and its extensions (e.g., Göbel et al., 2011; Patro et al., 2016), which predict that reading experience should affect the MNL.

These findings address two shortcomings of the only other experimental test of the effect of reading direction on the MNL. Dehaene and colleagues (1993; Experiment 8) found no effect of reading direction on the SNARC effect. In principle, this null result could have been due to an insufficient experimental manipulation, for two reasons. First, there was no training phase in Dehaene et al.'s experiment. Second, there was no manipulation check. Therefore, there is no evidence that the amount of exposure to mirror-reversed text that participants received in that experiment was sufficient to influence spatial mappings in their minds. In the current study, we (a) included a training phase to greatly increase participants' exposure to mirror-reversed text, and (b) included a manipulation check: Although reading training had no effect on the participants' MNLs, it significantly affected their MTLs. As such, the lack of an effect on the MNL in the present study cannot easily be attributed to a paucity of reading training. Nor can it be attributed to a lack of power: By combining data from the two number tasks (digit task and number word task), we had twice as much item-wise power to detect differences in space–number congruity effects as in space–time congruity effects. Still, reading training had no discernable effect on the MNL.

[7] In Casasanto and Bottini (2014; henceforth C&B), a few minutes of mirror-reversed reading reversed the direction of the MTL. Why did we observe a weakening but not a full reversal of participants' normal MTLs in our experiment? This difference cannot be attributed to a difference in the amounts of mirror-reversed reading that participants received in the two experiments, as reading experience was greater in our experiment than in C&B's. Rather, the difference in the results is likely attributable to a difference in the stimuli used to evaluate the MTL. The month names we used to test the MTL not only refer to different points in time—they also appear in different points in *space*: earlier months tend to appear to the left side of later months on calendars and other visual timelines. This consistent left-right spatial arrangement of month names provides an additional experiential basis for the MTL, and may have acted as a counterweight to our training manipulations in Experiments 1 and 3. By contrast, C&B's test of the MTL was free of this counterweight; participants classified phrases like "A year before" or "A year after," stimuli that refer to different points in time but, unlike months, have no conventional left-right spatial position. Without any graphical convention to anchor these stimuli in space, C&B's task may have been more sensitive than ours to changes in the direction of the MTL.

If reading does not affect the direction of the MNL, then what kind of experience does? According to the CORE principle, the MNL should be shaped by experiences that provide a correlation between space and numbers. Although reading text does not provide a clear space–number correlation, many other cultural practices do. In Experiment 2, we tested the effect of one such cultural practice on the direction of the MNL.

Experiment 2: Can Finger Counting Shape the MNL?

What kinds of experience spatialize numbers? Unlike the act of reading, the act of finger counting provides a correlation between numbers and space; during finger counting, different numbers are associated with different fingers, each with a unique ordinal position in left-right space. Therefore, the CORE principle predicts that finger counting should be among the experiences that can affect the direction of the MNL. On the basis of correlational evidence, some researchers have suggested that finger counting may play a role in directing the MNL (e.g., Wood & Fischer, 2008; see General Discussion) but to date there has been no experimental test of this proposal.

Here, we randomly assigned participants to count on their hands either left-to-right (rightward) or right-to-left (leftward) and then tested their space–number congruity effects using two standard SNARC tasks (one of which was used to measure space–number congruity effects in Experiment 1). Experiment 2 had two goals. The first goal was to conduct a first test of whether finger counting can play a causal role in determining the direction of the MNL. The second goal was to rule out a potential skeptical interpretation of Experiment 1's results. In our first experiment, reading experience affected the MTL but not the MNL, as predicted by CORE. In principle, however, this pattern could indicate that the MNL is more firmly entrenched in long-term memory than the MTL, and is therefore less susceptible to brief laboratory training experiences (but see Fischer et al., 2010). If the MNL is simply harder to change than the MTL, then manipulating finger-counting direction in Experiment 2 should be no more effective than manipulating reading direction was in Experiment 1. Alternatively, if the MNL is selectively shaped by experiences that spatialize numbers, as predicted by CORE, then participants in Experiment 2 should show a standard SNARC effect after counting rightward and a weakened (or reversed) SNARC effect after counting leftward.

Method

Participants. Sixty-four right-handers from the University of Chicago and the Chicago area participated for payment or course credit. Half were randomly assigned to the leftward counting condition ($n = 32$) and the other half to the rightward counting condition ($n = 32$).

Materials and procedure. Participants performed a two-part experiment in which a training phase was followed by a test phase. In the training phase, participants counted on their fingers according to one of two randomly assigned patterns (see Figure 1, center panel). In the test phase, all participants performed two standard tests of the SNARC effect, a parity-judgment task and a magnitude-judgment task, with the order of these tasks counterbalanced across subjects using a Latin square design.

During both the training and test phases, participants sat at a desk in front of an Apple iMac computer. Instructions and stimuli were presented in white text on a black background in the center of the screen. All numbers were displayed as Arabic numerals.

Before training, participants' spontaneous finger-counting habits were assessed using both an implicit and an explicit task. In the implicit task (adapted from Lucidi & Thevenot, 2014), the experimenter read aloud three sentences and asked participants to report the number of syllables in each. Participants often spontaneously used their fingers to arrive at the solution. In the explicit task, participants were asked to count on their fingers from 1 to 10, as they normally would, while speaking the numbers aloud. Their counting patterns were recorded by a video camera and documented on paper forms out of their sight.

Training phase. At the beginning of training, the experimenter stood to the left of the participant, facing the same direction, and demonstrated the randomly assigned finger-counting pattern once. Participants then repeated the pattern once in tandem with the experimenter and then once on their own. In the rightward counting condition, participants counted from left to right, starting with the left thumb and ending with the right thumb. In the leftward counting condition, participants counted in the opposite direction, starting with the right thumb and ending with the left thumb. Both hands were kept in the supine position (palms up) during all counting tasks.

After participants were familiarized with the leftward or rightward finger-counting pattern, they practiced the pattern during three computer-based training tasks (Tasks A, B, and C). In all three tasks, the integers 1 through 10 were displayed in the center of the screen. Participants were required to represent the displayed number on their fingers using the finger-counting pattern they had just practiced. Instructions appeared on the screen at the beginning of each task. In Task A, participants started with their hands closed and counted up to the number displayed, saying each number aloud while extending the corresponding finger. In Task B, participants started with their hands closed and extended the set of fingers corresponding to the number displayed on the screen (all at once) while saying the number aloud. In Task C, participants held their hands open and counted up to the number displayed, saying each number aloud while they wiggled the corresponding finger. Using three tasks rather than one was intended to encourage participants to stay engaged in the repetitive task. After the participant successfully completed each trial, the experimenter advanced to the next trial by pressing a key on a keyboard out of sight of the participant. The numbers 1 through 10 were presented in random order three times in each task and this training sequence was repeated six times with a brief break after the third round (i.e., ABC, ABC, ABC, break, ABC, ABC, ABC), composing a total of 540 training trials. Training lasted about 25 min in both counting conditions, and was recorded by a digital video camera positioned out of sight of participants.

Test phase. After training, participants performed two standard tests of the SNARC effect: a parity judgment task (Dehaene et al., 1993) and a magnitude judgment task (as in Experiment 1). The order of these tasks was counterbalanced across participants. We reasoned that using both parity and magnitude judgments provided a better index of the MNL than either task, alone, and provided the opportunity for an experiment-internal replication of the effect of finger training on the SNARC effect. In each task, participants were instructed to respond as quickly and accurately as possible to the numbers on the screen by pressing one of two keys (the "a" key and the apostrophe key on the English-US QWERTY keyboard), each covered by a yellow sticker.

In the parity judgment task, participants were instructed to press the yellow key on the left for odd numbers and the yellow key on the right for even numbers for one block of trials. In the other block this mapping was reversed, and the order of blocks was counterbalanced across participants. Each of eight digits (1 through 9 except 5) was presented eight times in random order, yielding 64 trials per block. Each trial began with a fixation cross for 500 ms, after which the digit appeared and remained on the screen until the participant responded. As in Experiment 1, participants used their left index finger to press the left key and their right index finger to press the right key.

The materials and procedures used in the magnitude judgment task were identical to those used in the parity judgment task, with the exception of the task instructions. In one block, participants were instructed to press the yellow key on the left for numbers less than 5 and the yellow key on the right for numbers greater than 5, and in the other block this response mapping was reversed. Block order was counterbalanced across participants.

In total, each participant completed 256 test trials across four blocks (two parity judgment blocks and two magnitude judgment blocks). The order of both blocks and tasks was counterbalanced across participants using a Latin square design.

After testing, participants were debriefed to determine whether they were aware of the experimental hypothesis, and they completed a language history questionnaire and the EHI.

Results

The raw data and analysis scripts for Experiment 2 are available in an OSF archive at https://osf.io/v4em9/.

Exclusions. Five participants guessed the purpose of the training, and were replaced. Three participants failed to follow instructions in the parity task and three other participants failed to follow instructions in the magnitude task; these data were excluded.

Spontaneous finger-counting habits. The proportion of left-starters and right-starters did not differ significantly across training conditions, according to both the implicit and the explicit assessments (Fisher's exact tests, $p = 1$). Therefore, any effect of finger-counting training cannot be due to incidental differences in participants' spontaneous finger-counting habits.

Accuracy. Overall, accuracy was above 96%. According to repeated-measures binomial logistic regressions with random slopes and intercepts for subjects, the error rate did not differ significantly between the rightward counting condition (4.08% ±0.20 *SEM*) and the leftward counting condition (3.89% ±0.19 *SEM*), $\chi^2(1) = .24$, $p = .62$. The error rate in the parity judgment task (4.51% ±.21) was significantly higher than in the magnitude judgment task (3.46% ±.19 *SEM*), $\chi^2(1) = 6.48$, $p = .01$, but this difference was very small (about 1%). Inaccurate trials (3.99% ±0.14 *SEM*) were excluded from the RT analyses.

RT analyses. To evaluate space–number congruity effects, we conducted the same lmer models that we used in Experiment 1. RTs were predicted by response hand, training condition (where appropriate), and ordinal position of numbers, with random slopes and intercepts for subjects. In all tests, RTs were inverse-transformed to approximate a normal distribution of residuals, according to the results of Box Cox tests (Osborne, 2010).

To remove outliers, we followed the procedure from Experiment 1, first excluding RTs slower than 2,000 ms (0.93%), and then removing RTs more than 2.5 *SD*s from subject means.

Parity task. RTs greater than 2.5 *SD*s from subject means were removed (2.97% of accurate responses). In the rightward counting condition, participants showed a highly significant standard SNARC effect, $\chi^2(1) = 19.79$, $p = .00009$ (slope = −11.81 ms/position ±2.19 *SEM*). Although participants in the leftward counting condition also showed a significant standard SNARC effect, $\chi^2(1) = 4.96$, $p = .02$ (slope = −4.98 ms/position ±2.13 *SEM*), of primary interest this effect was significantly reduced, $\chi^2(1) = 4.38$, $p = .04$ (Figure 3, left). Finger-counting training changed the MNL in the parity task, as predicted by the CORE principle.

Magnitude task. RTs greater than 2.5 *SD*s from subject means were removed (2.88% of accurate responses). In the rightward counting condition, participants again showed a highly significant standard SNARC effect, $\chi^2(1) = 27.20$, $p = .000002$ (slope = −16.61 ms/position ±1.57 *SEM*). Although participants in the leftward counting condition also showed a significant standard SNARC effect, $\chi^2(1) = 5.32$, $p = .02$ (slope = −7.62 ms/position ±1.75 *SEM*), again this effect was significantly reduced, $\chi^2(1) = 31.40$, $p = .0000002$ (Figure 3, right). Finger-counting training changed the MNL in the magnitude task, as predicted by the CORE principle.

Cross-experiment comparison of space–number effects. Did the effect of finger counting on the MNL differ from the (null) effect of reading training? To find out, we compared performance in the task that was performed in both Experiments 1 and 2 (i.e., magnitude judgments of Arabic numerals). These RTs were transformed using an inverse square-root transformation and entered into an lmer model that included Experiment as a fixed effect. The effect of finger-counting training in Experiment 2 was reliably stronger than the (null) effect of reading training in Experiment 1, $\chi^2(1) = 15.61$, $p = .0008$. In short, the MNL was changed significantly more by finger-counting training than by reading training.

Discussion

A few minutes of finger counting significantly changed English speakers' implicit space–number mappings. Whereas training with a rightward finger-counting routine produced a standard SNARC effect, training with a leftward finger-counting routine reliably weakened this effect, in two tests of space–number associations. Although previous studies have demonstrated a correlation between finger counting and SNARC effects (e.g., Fischer, 2008; Riello & Rusconi, 2011), the present results provide the first evidence that finger counting is among the experiences that can play a causal role in shaping the MNL.[8]

The results of Experiment 2 also rule out a potential skeptical interpretation of Experiment 1's results. In principle, reading experience could have influenced the MTL but not the MNL because the MNL is more firmly entrenched in long-term memory than the MTL, and less susceptible to brief laboratory training experiences.

[8] These results corroborate the results of Pitt and Casasanto (2014), which showed a similar finger-counting training effect in a smaller independent sample.

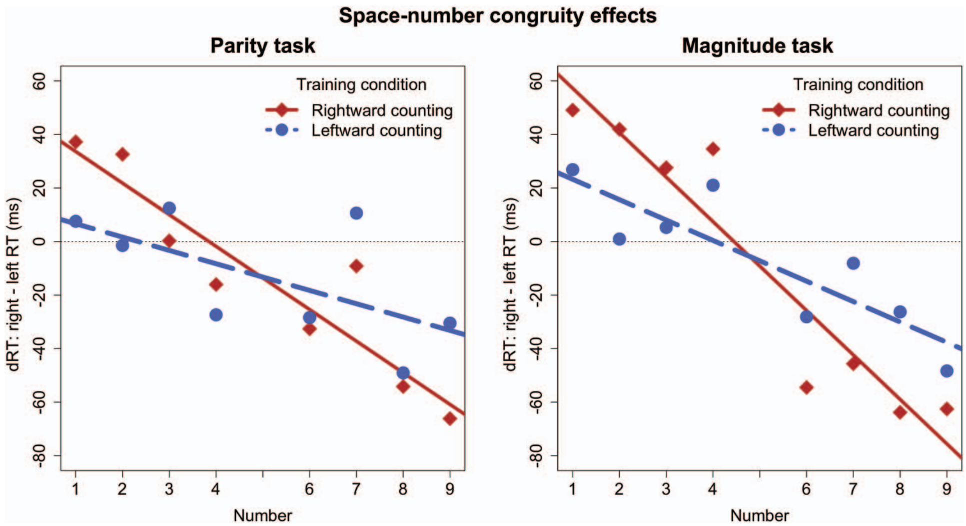

Figure 3. Results of Experiment 2. In both the parity task (left) and magnitude task (right), participants showed significant standard space–number congruity (SNARC) effects after counting rightward (solid red lines). These effects were significantly reduced after counting leftward (dashed blue lines). See the online article for the color version of this figure.

However, not only is this skeptical account difficult to motivate theoretically, it is also inconsistent with the results of Experiment 2 (see also Fischer et al., 2010). Right-to-left reading training lasted about 36 min on average, whereas right-to-left finger counting only lasted about 25 min; the dosage of training cannot explain the difference between the experiments, since participants received more reading training than finger counting training (about 44% more). Rather, the pattern of results suggests that both the MTL and the MNL are susceptible to brief training interventions, so long as those interventions introduce the right kind of experience: correlations between space and time (found in reading), or correlations between space and numbers (found in finger counting).

In finger counting, each number is associated not only with a position in left-right space, but also with a specific finger. Rather than a mapping between numbers and space, could our finger-counting manipulation have trained a *manual* number line, in which each number corresponds to a different finger?

Our data suggest that the answer is no. During training, participants counted with their hands in the supine position (palms up). During testing, however, they turned their hands over to the prone position (palms down), inverting the left-right position of the fingers on each hand. If participants had mapped numbers to particular fingers (rather than to positions in space) then their "manual number lines" would not yield a coherent mapping of numbers to space across the two hands. For example, in the leftward counting condition, when participants' hands were prone the numbers 1 and 10 (the thumbs) would be adjacent to one another in the middle of the line, and 5 and 6 (the pinkies) would be separated from each other at the right and left outer ends of the line. RTs corresponding to this incoherent manual number line would not follow the linear pattern typical of SNARC data that we predicted and found. In sum, the SNARC effects we report here suggest that finger counting trained participants to associate numbers with space (via the fingers), and not with the fingers, themselves.

These training results, therefore, are consistent with previous data suggesting that the MNL is anchored in external spatial coordinates (Dehaene et al., 1993) rather than hand-based coordinates (at least in sighted people, see Crollen, Dormal, Seron, Lepore, & Collignon, 2013). One function of the fingers during finger counting, then, may be to index space, which creates a generalizable MNL: one that is continuous (from 1 to 10), and robust to changes in the positions of the hands.

These results support the CORE principle, according to which finger counting (an experience that spatializes number) should affect the MNL. Yet, these results are also consistent with the reading/writing/scanning hypothesis, which posits that, beyond reading and writing, other "spatially organized sequences of movement" (Patro et al., 2016, p. 4) like finger counting should affect the MNL. Taken together, however, the results of Experiments 1 and 2 are only consistent with CORE; only CORE predicts that finger-counting should affect the MNL (as shown in Experiment 2) and that reading should not (as shown in Experiment 1). We further distinguish these hypotheses in Experiment 3.

Experiment 3: The MTL and MNL Are Shaped by Different Aspects of Experience

Together, the results of Experiments 1 and 2 support CORE and disconfirm the reading/writing hypothesis and its extensions, according to which reading experience should have a "pronounced" (Patro et al., 2016, p. 4) effect on the MNL. However, the inferences drawn from Experiments 1 and 2 rely, in part, on CORE predicting no influence of reading direction on the MNL: a null effect in one condition. For Experiment 3, we developed a finger counting protocol in which CORE and the competing hypotheses predict distinct patterns of (significant) training effects in all conditions.

Here, we independently manipulated the correlation between space and time and the correlation between space and number. All participants counted *down* on their fingers (from a target number down to 1), and were randomly assigned to progress across their fingers either to the right (i.e., ending on the right thumb) or to the left (i.e., ending on the left thumb; Figure 1, right). Normally, when counting *up* on the fingers (e.g., from 1 to 10, as in Experiment 2), time progresses in the same direction that number increases: Both go to the right, or both go to the left.[9] By contrast, when counting *down* on the fingers, time and number are spatialized in opposite directions: When time progresses to the right number increases to the left, and vice versa. For this reason, counting down on the fingers allowed us to evaluate the independent (and opposing) effects of a single training experience on the MTL and the MNL, and to distinguish CORE from the competing proposals.

If the MTL is selectively shaped by aspects of experience that spatialize time and the MNL is selectively shaped by aspects of experience that spatialize numbers, as the CORE principle dictates, then each training condition (e.g., counting down to the left) should have *opposite effects* on participants' space–time and space–number associations. For participants who counted down to the right (10⟶1), time progressed rightward across the fingers as the numbers decreased, causing them to count smaller numbers on their right hand and larger numbers on their left. Therefore, this training should strengthen (or maintain) the standard MTL but weaken (or reverse) the standard MNL. Conversely, for participants who counted down to the left (1⟵10), time progressed leftward across the fingers as the numbers decreased, causing them to count smaller numbers on their left hand and larger number on their right. Therefore, this training should weaken (or reverse) the standard MTL but strengthen (or maintain) the standard MNL.

The reading/writing/scanning hypothesis makes a distinct prediction from CORE. If "all spatially oriented activities" (Patro et al., 2016, p. 4) have similar effects, and if the direction of the MTL and MNL both follow the direction of "spatially organized sequences of movement" (ibid.), then both the MTL and MNL should follow the direction of movement across the fingers; counting down from left to right should cause both the MTL and the MNL to progress from left to right, whereas counting down from right to left should cause both the MTL and the MNL to progress from right to left. In sum, the reading/writing/scanning hypothesis predicts that training should change the MTL and MNL in the *same direction*; by contrast, CORE predicts that each training experience should change the MTL and MNL in *opposite directions*, resulting in a double dissociation between the spatial mappings (MTL, MNL) and the training conditions (counting down to the left, counting down to the right).

Method

Participants. One hundred twenty-eight right-handers from the University of Chicago and the Chicago area participated for payment or course credit. Half were randomly assigned to count down to the right (10⟶1) and the other half to count down to the left (1⟵10; Figure 1, right panel).

Materials and procedure. Participants performed a two-part experiment in which a training phase was followed by a test phase. To avoid any effects of reading, all instructions and stimuli were prerecorded and presented auditorily. Participants were not exposed to any written text during either training or testing.

Before training, participants' spontaneous finger-counting habits were assessed using the same two methods used in Experiment 2.

Training phase. The training procedure was similar to that of Experiment 2, but with adaptations for "downward" counting and auditory stimuli. In the counting-down-to-the-right condition (10⟶1), participants counted down from left to right, starting with the left thumb and ending with the right thumb. In the counting-down-to-the-left condition (1⟵10), participants counted down in the opposite direction, starting with the right thumb and ending with the left thumb (see Figure 1, right panel).

After participants were familiarized with the leftward or rightward finger-counting pattern, they practiced the pattern during a computer-based training task. In each trial of this task, participants heard a number between one and 10 spoken aloud from the computer speakers. With their hands open and palms up, participants counted aloud from the number they heard down to one, wiggling each of the corresponding fingers, one at a time, according to the pattern they had just learned. After the participant successfully completed each training trial, the experimenter advanced to the next trial by pressing a key on a keyboard out of sight of the participant. Participants heard the 10 number words (1–10) in random order 16 times and then they took a short break before completing another 16 rounds of training. After these 32 rounds, participants were instructed to do the same counting task but "as quickly and accurately as possible" as a "test" of the counting pattern they had been practicing. This alleged test phase (which actually served as four more rounds of training) was designed to discourage participants from drawing a connection between the training phase and the actual test phase to follow. In all, participants completed 360 training trials, which took about 22 min on average in both counting conditions.

Test phase. The test phase was similar to that of Experiment 1, but with adaptations for auditory stimuli. All instructions and stimuli were presented auditorily through computer speakers. In the number task, participants heard the numbers one through 10 (except five) and classified each as either less than or greater than five by pressing one of two lateralized response keys. In the month task, participants heard the names of the months from February to October (except June) and classified each as either earlier than or later than June by pressing one of the two lateralized response keys. In each block, the eight unique stimuli (number words or month names) were played in random order 12 times, composing 192 trials per task. Participants were told to respond "as quickly and accurately as possible." To eliminate very slow responses, each trial ended automatically 1,500 ms after stimulus onset with an auditory alert (if no response was given), following a previous auditory SNARC test by Nuerk, Wood, and Willmes (2005). The

[9] The act of counting any array of objects spatializes both time and number. Some studies have sought to test spatial-numerical associations by evaluating the direction in which participants counted a lateral array of objects (e.g. Göbel et al., 2018). However, the way in which people count objects may reflect participants MTL, their MNL, or both. Therefore, the direction in which participants count is not a valid measure of spatial-numerical associations (in the present study we use counting as a *training experience*, not as a *test* of the MNL).

order of response mappings was crossed with the order of tasks and counterbalanced across participants.[10]

Results

The raw data and analysis scripts for Experiment 3 are available in an OSF archive at https://osf.io/92jvf/.

Exclusions. Eight participants who guessed the purpose of training and seven who failed to follow instructions were replaced.

Spontaneous finger-counting habits. The proportion of left-starters and right-starters did not differ significantly across training conditions, according to both the implicit and the explicit assessments (Fisher's exact tests, *ps* > .25).

Accuracy. Overall, accuracy was nearly 95%. According to repeated-measures binomial logistic regressions with random slopes and intercepts for subjects, the error rate in the counting-down-to-the-right condition (4.68% ±.13 *SEM*) was marginally lower than in the counting-down-to-the-left condition (5.66% ±.15 *SEM*), $\chi^2(1) = 2.91$, $p = .09$. The error rate in the Time task (6.34% ±.16 *SEM*) was significantly higher than in the Number task (4.00% ±.13 *SEM*), $\chi^2(1) = 53.32$, $p < .0001$. Error trials (5.17%) were excluded from the RT analyses.

RT analyses. To evaluate the effects of training on the space–number and space–time associations, we used the same lmer models used in Experiments 1 and 2. RTs were predicted by response hand, training condition (where appropriate), and ordinal position of months or numbers, with random slopes and intercepts for subjects. For each model, we first used a Box Cox test to determine how best to transform the data to approximate a normal distribution of residuals (Osborne, 2010).

Space–time associations. RTs greater than 2.5 *SD*s from subject means were removed (2.40% of accurate responses). RTs were then transformed using a square-root transformation to approximate a normal distribution of residuals. In the counting-down-to-the-right condition (10→1), in which participants started on the left and ended on the right, the space–time congruity effect was significant, $\chi^2(1) = 9.52$, $p = .002$, indicating a reliable standard MTL (slope = −7.75 ms/position ±1.47 *SEM*). In the counting-down-to-the-left condition, the space–time congruity effect did not differ significantly from zero (1←10; $\chi^2(1) = .89$, $p = .35$; slope = −2.41 ms/position ±1.68 *SEM*). Of primary interest, the space–time congruity effect was significantly stronger when time progressed to the right during training (10→1) than when it progressed to the left (1←10), $\chi^2(1) = 8.46$, $p = .003$ (Figure 4, left), as predicted by the CORE principle. The way in which time was spatialized across the fingers during counting training reliably changed the MTL, despite the spatialization of numbers in the opposite direction.[11]

Space–number associations. RTs greater than 2.5 *SD*s from subject means were removed (2.58% of accurate responses). RTs were then transformed using an inverse square-root transformation to approximate a normal distribution of residuals. In the counting-down-to-the-left condition, in which participants counted smaller numbers on the left and larger numbers on the right (1←10), the SNARC effect was significant, $\chi^2(1) = 15.61$, $p = .0008$ (slope = −10.27 ms/position ±1.38 *SEM*), indicating a reliable standard MNL. In the counting-down-to-the-right condition, in which participants counted smaller numbers on the right and larger numbers on the left (10→1), the SNARC effect was also significant, $\chi^2(1) = 6.09$, $p = .01$ (slope = −6.79 ms/position ±1.39 *SEM*). Of primary interest, the SNARC effect was significantly stronger when numbers increased from left to right (1←10) than when they increased from right to left (10→1), $\chi^2(1) = 10.46$, $p = .001$ (Figure 2, right), as predicted by the CORE principle. The way in which numbers were spatialized across the fingers during counting training reliably changed the MNL, despite the spatialization of time in the opposite direction.

Comparison of space–number and space–time effects. To compare the effect of training condition on space–number and space–time congruity effects, we conducted an lmer model on transformed RTs with response hand, ordinal position of months or numbers, training condition, and task as predictors, with random slopes and intercepts for subjects. RTs were log transformed to approximate a normal distribution of residuals. Training had significantly different effects on space–number and space–time congruity effects, $\chi^2(1) = 17.31$, $p = .0003$. The finger counting training changed the MNL and MTL in opposite directions, as predicted by the CORE principle.

Discussion

Here we gave participants an experience in which time and numbers were spatialized in opposite directions on their fingers and then we measured the effects of this training on their MTL and MNL. The training had opposite effects on the MTL and the MNL: The MTL differed according to the way time was spatialized across the fingers (despite the countervailing spatialization of numbers) whereas the MNL differed according to the way numbers were spatialized across the fingers (despite the countervailing spatialization of time).

These results show that the MTL and MNL are shaped by different aspects of experience, and provide strong support for the CORE principle. Furthermore, these results are incompatible with previous attempts to explain the direction of the MNL, which posit that the MNL should follow the direction of movement through left-right space (Göbel et al., 2011; Patro et al., 2016); here, the MNL followed the spatialization of numbers, *despite* the direction of movement across the fingers.

[10] In an attempt to minimize the total number of participants needed for a balanced design in Experiment 3, we asked participants to perform both the month task and the number task in the same testing session, with the order of tasks counterbalanced across participants and crossed with training condition. However, after collecting the planned sample of 64 subjects, a control analysis showed a task order effect: The effect of training on the month task depended on whether participants performed the month task before or after the number task, $\chi^2(1) = 5.68$, $p = .02$. To avoid this effect of task order, which was irrelevant to the experimental hypotheses, we made Task a between-subjects variable by analyzing the data from subjects' first task only; this change required us to double the sample to maintain 32 subjects per cell (as in Experiments 1 and 2), therefore the sample size was increased from 64 to 128 subjects (see the online supplemental materials for details of the task order effect).

[11] This reliable effect on the MTL was found despite the fact that time was less salient in our finger-counting training than numbers; whereas participants spoke number words aloud during the training, the passage of time remained implicit. This finding is consistent with previous studies showing that the passage of time is tracked spontaneously and unconsciously (Casasanto & Bottini, 2014).

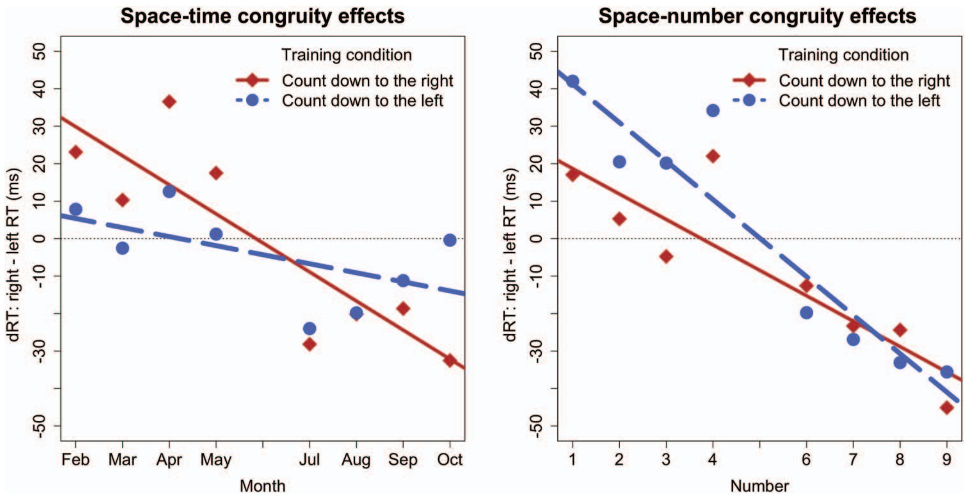

Figure 4. Results of Experiment 3, in which finger-counting training had opposite effects on the MTL and MNL. Left: In the month task, participants showed a significant standard space–time congruity effect after counting down to the right (solid, red line) and a significantly reduced effect after counting down to the left (dashed, blue line). Right: In the number task, participants showed a significant space–number congruity (SNARC) effect after counting larger numbers on the right (dashed, blue line) and a significantly reduced effect after counting larger numbers on the left (solid, red line). See the online article for the color version of this figure.

General Discussion

In three experiments, we tested the CORrelations in Experience (CORE) principle by comparing the effects of different training experiences on the MTL and MNL. According to CORE, abstract conceptual domains are spatialized in people's minds the way they are spatialized in their experience. Whereas alternative accounts posit that the mental timeline (MTL) and mental number line (MNL) should be shaped by the same set of experiences, and by reading experience in particular, CORE predicts that the MTL and MNL should be shaped by different aspects of cultural experience. In Experiment 1, reading text, an experience that spatializes time but not numbers, influenced the direction of the MTL but not the MNL. After reading normal English text, participants showed the space–time and space–number associations typical of Westerners. After reading mirror-reversed text (from right to left), participants' space–time associations were significantly weakened but their space–number associations were unchanged. In Experiment 2, finger-counting experience, which spatializes numbers, reliably influenced the direction of the MNL. Participants who counted on their fingers from left to right showed strong standard space–number congruity effects whereas those who counted from right to left showed significantly weakened effects. In Experiment 3, the MTL and MNL were changed in opposite directions by the same training experience. Space–time associations changed according to the direction in which finger counting spatialized time, whereas space–number associations changed according to the direction in which the same training experience spatialized numbers. Across experiments, the CORE principle predicted which aspects of experience did—and did not—influence how number and time were spatialized in people's minds.

Reassessing the Reading/Writing Hypothesis and Its Extensions

Our findings are incompatible with the proposals that have been advanced previously to explain the direction of the MNL (i.e., the reading/writing and reading/writing/scanning hypotheses). Experiment 1 challenges these proposals because they include reading in the set of experiences that should shape the MNL. The noneffect of reading training on the MNL that we found in Experiment 1 cannot be attributed to the "stubbornness" of the MNL, which was reliably changed by a smaller amount of finger-counting training in Experiment 2.

Experiment 3 also challenges the two main claims of the previous proposals: First, the MNL should be shaped by "spatially directional scanning of visual materials" (Shaki & Fischer, 2008, p. 596); second, the MTL and MNL should depend on the same set of "spatially organized sequences of movement" (Patro et al., 2016, p. 4). To support these claims, both the MTL and the MNL should have followed the direction in which participants in Experiment 3 scanned/moved across their fingers; they did not. Rather, the MNL followed the spatialization of numbers (despite the direction of movement), and the MTL followed the direction of movement (despite the spatialization of numbers), producing the double dissociation predicted by the CORE principle.

Experiential Bases of the MTL

Reading experience. Although researchers have long assumed that the MTL is shaped by "the direction of writing" (Tversky et al., 1991, p. 517), the reason has remained unclear. For example, in explaining the direction of the MTL in Westerners, Bonato et al. (2012, p. 2260) argue that "the preference for the left-to-right order is a consequence of the tendency to 'align' events according to writing direction." Reading/writing experience has been said to shape the MTL via "spatial attention" (ibid, p. 2261), "spatial-directional biases" (Patro et al., 2016, p. 5), and "attentional search processes" in working memory (Abrahamse, van Dijck, Majerus, & Fias, 2014, p. 3). Although it is clear that visuomotor activities like reading and writing involve shifts of attention, it is it not clear from these explanations *why* shifts of attention should affect mental representations of time. CORE provides a clear reason: Reading shapes the MTL because it provides a correlation between space and time; as readers shift their attention (and gaze) from one side of the page to the other, this act produces a correlation between points in space and points in time in the readers' experience (see also Casasanto & Bottini, 2014). Likewise, other experiences that provide such a space–time correlation can also shape the MTL, as finger counting did in Experiment 3. In this way, the present findings not only confirm *that* reading can shape the MTL—they also clarify *why* reading shapes the MTL.

Beyond reading experience. Beyond reading experience and finger counting, what other experiences can shape the MTL? According to the CORE principle, any activity that provides a correlation between points in time and points in space that are arrayed along a spatial axis (e.g., rightward, leftward, upward, or downward; see Casasanto & Bottini, 2014) should affect the direction of the MTL. This space–time correlation is found in visual activities like reading English as well as nonvisual activities like reading Braille. Accordingly, congenitally blind Italians show left-to-right MTLs that are indistinguishable from sighted controls, despite their lack of visual experience (Bottini, Crepaldi, Casasanto, Crollen, & Collignon, 2015).

Space–time mappings may also be shaped by seeing spontaneous gestures about time, which follow gesturers' implicit mental timelines (Casasanto & Jasmin, 2012; Cooperrider & Núñez, 2009; Núñez & Sweetser, 2006), and by explicit spatial representations of time. For example, in Western cultures we place Monday to the left of Tuesday on calendars, and the year 1999 to the left of 2000 on timelines and graphs. By systematically displaying earlier events on one side and later events on the other, many cultural artifacts provide the kind of experience that, according to CORE, should be capable of shaping the MTL. Given that depictions of time tend to follow the direction of reading and writing across cultures, experiencing temporal gestures, calendars, graphs, and timelines should reinforce the same culture-specific space–time mappings as reading and writing, per se.

Experiential Bases of the MNL

Finger counting. Experiments 2 and 3 showed that finger counting is among the experiences that can shape the MNL. These findings are consistent with "manumerical" accounts of numerical cognition, according to which the fingers play an important functional role in the representation and manipulation of numbers (Andres & Pesenti, 2015; Fischer & Brugger, 2011; Wood & Fischer, 2008; see also Di Luca & Pesenti, 2011; Rinaldi, Di Luca, Henik, & Girelli, 2016). These accounts are supported by a variety of studies using behavioral methods (Badets, Pesenti, & Olivier, 2010; Di Luca et al., 2006; Di Luca & Pesenti, 2011; Domahs, Krinzinger, & Willmes, 2008; Domahs, Moeller, Huber, Willmes, & Nuerk, 2010; Fayol, Barrouillet, & Marinthe, 1998; Gracia-Bafalluy & Noël, 2008; Noël, 2005; Riello & Rusconi, 2011; Sixtus, Lindemann, & Fischer, 2018; Sixtus, Fischer, & Lindemann, 2017; Sixtus et al., 2018), neurostimulation (Rusconi, Walsh, & Butterworth, 2005; Sato, Cattaneo, Rizzolatti, & Gallese, 2007), and brain imaging (Andres, Michaux, & Pesenti, 2012; cf. Andres, Seron, & Olivier, 2007). These findings have lead some researchers to posit that " Spatial–numerical associations, previously attributed to reading habits, may at least partly have their origin in finger counting routines" (Fischer, Kaufmann, & Domahs, 2012, p. 1). If so, then finger counting should not only affect the MNL in the lab, as our results show it can, it should also influence the direction of the MNL across cultures. Yet according to the available evidence, the direction of the MNL is not strongly correlated with the direction of finger counting (Di Luca et al., 2006; Fischer, 2008; Lindemann, Alipour, & Fischer, 2011; Sato et al., 2007; Sato & Lalain, 2008). Why not?

We suggest four reasons why finger-counting habits may covary only loosely with the direction of the MNL across cultures. First, finger counting routines depend on context; even in a culture with established finger-counting conventions, people's actual finger-counting behavior may depend on how high they plan to count and for whom they are counting (i.e., themselves or an observer), among other factors (Bender & Beller, 2012). Second, finger counting routines depend in part on ergonomic constraints. For example, holding up only the thumb and pointer finger is physically easier than holding up only the pinky and ring fingers, which could lead people to count from thumb to pinky, even when this causes them to spatialize numbers in different directions on each hand. Therefore, many finger-counting routines, even those that start on one hand and end on the other hand, may provide an imperfect correlation between numbers and space. Third, finger-counting patterns are difficult to measure reliably, and different tests yield different patterns. In this study, we tested participants' finger-counting habits with an implicit assessment designed to elicit spontaneous finger-counting (i.e., syllable counting; Lucidi & Thevenot, 2014). However, many other studies (including cross-cultural studies) have simply relied on participants' ability to report their own finger-counting habits explicitly. Implicit and explicit assessments yield different counting behaviors (Lucidi & Thevenot, 2014), complicating the ability to detect any correlation between finger-counting habits and the MNL. Finally, finger counting is only one of many experiences that spatialize numbers in left-right space, and other experiences may provide space–number correlations that are more reliable, salient, or frequent.

Beyond finger counting. What other experiences can shape the MNL? According to the CORE principle, any experience that consistently spatializes numbers should affect the MNL. People experience numbers in space not only as they count on their fingers, but also when they see written numbers arrayed in space. Cultural artifacts like rulers, calendars, graphs, and computer keyboards present written numbers in increasing order either from left to right or from right to left.[12]

[12] Some cultural artifacts, like calendars and timelines, spatialize both time and numbers. Can using such artifacts shape both the MTL and the MNL? Yes, according to the CORE principle, a single experience (e.g. using a calendar) can affect multiple mappings at once, so long as the experience spatializes the relevant domains. Such a pattern is demonstrated in Experiment 3, in which a single experience had independent and opposite effects on the MTL and MNL.

Can experience with written numbers affect the MNL, as finger counting did here? Yes. In Fischer et al. (2010), participants read recipes in which numbers were systematically arranged on the page in one of two ways. When smaller numbers appeared on the left and larger numbers appeared on the right (e.g., Beat 3 eggs in a large mixing bowl, adding 6 tbsp salt.), English-speaking participants showed a standard SNARC effect. When the spatialization of numbers on the page was reversed (e.g., Beat 6 eggs in a large mixing bowl, adding 3 tbsp salt.), this SNARC effect was significantly weakened. The spatialization of numbers on the page had an analogous effect on Israeli participants who read the sentences in Hebrew, from right to left. In both groups, the SNARC effects were modulated by the arrangement of smaller and larger numbers on the page. This finding lends further experimental support to the claim, derived from the CORE principle, that the MNL is shaped by experiences that spatialize numbers, no matter whether they are arrayed across the fingers or across the page.

Explaining cross-cultural variation in the MNL. Beyond the laboratory, culture-specific conventions for reading and writing *numbers* (but not for reading and writing text per se) explain the variation in the MNL that has been observed across cultures. This variation is clearest when comparing Westerners with Arabic-speakers, who show reversed SNARC effects (Maier et al., 2015; Shaki et al., 2009; Shaki & Fischer, 2012; Zebian, 2005). This cross-cultural difference has often been interpreted as (correlational) evidence for the reading/writing hypothesis, because people in these cultures read text in different directions. However, people in these cultures also have different conventions for reading and writing *numbers*.

For Westerners, numbers are written from left to right on a variety of culture-specific artifacts (e.g., graphs and charts, computer keyboards, kindergarten walls, etc.) This explicit spatialization of numbers is also present in multidigit numbers, in which larger numbers (e.g., "9") tend to appear more frequently on the right and smaller numbers (e.g., "1") tend to appear more frequently on the left (this pattern is known as the first-digit law; Benford, 1938). Conversely, many Arabic speakers write both numerals and number words from right to left and therefore tend to encounter smaller numbers on the right and larger number on the left.[13] These cultural conventions for reading and writing numbers cause Westerners and Arabic-speakers to see numbers arrayed differently in space. Therefore, when comparing this subset of cultures, the direction of the MNL can be explained either on the basis of written numbers—consistent with CORE—or on the basis text generally, because numbers and text are written in the same direction.

However, when considering the full range of available data, only CORE can explain the observed pattern of cross-cultural variation in the MNL. Hebrew-speaking Israelis provide a critical test case because they read and write text like Arabic-speakers (from right to left), but they read and write numerals like Westerners (from left to right). If the direction of the MNL were determined solely (or even primarily) by reading/writing text, then Hebrew-speakers should show right-to-left SNARC effects like Arabic-speakers. They do not. Rather, the only statistically significant SNARC effects that have been found in Israelis look like those of Westerners, consistent with the direction in which Israelis write numerals and number words in Hebrew, but inconsistent with the way they read and write text, in general (Feldman et al., 2019; Fischer & Shaki, 2016; Shaki & Gevers, 2011; Zohar-Shai et al., 2017). These significant SNARC effects in Israelis are predicted by CORE, but not by any known versions of the reading/writing/scanning hypothesis (which do not distinguish the reading and writing of numbers from other reading/writing/scanning activities).

In addition to showing Western-like SNARC effects, Hebrew speakers sometimes show "flat" SNARC effects (i.e., slopes that do not differ significantly from zero; e.g., Fischer & Shaki, 2014; Shaki et al., 2009). In an attempt to explain these null effects, some researchers have proposed that perhaps "reading habits for both words and numbers contribute to the spatial representation of numbers" (Shaki et al., 2009, p. 328). On this hybrid account, flat SNARC effects in Hebrew-speakers may be the result of "their conflicting spatial associations for words and numbers" (ibid., p. 329).

However, the null findings in Hebrew speakers can be explained without positing such a hybrid account, on the basis of the spatialization of numbers alone. When Hebrew-speaking Israelis write numerals, they use the same Arabic numerals that Westerners use (e.g., 1, 2, 3); therefore, like Westerners, they tend to encounter these numerals arranged in increasing order from left to right. Critically, this space–number mapping reverses when Israelis read or write *number words* (e.g., one, two, three): Words denoting smaller numbers tend to appear on the right and words denoting larger numbers tend to appear on the left (see Moeller, Shaki, Göbel, & Nuerk, 2015). Therefore, whereas Westerners experience a consistent number mapping from left to right (when they read numbers) and Arabic speakers experience a consistent number mapping from right to left, regardless of notation, Israelis experience two number mappings that go in opposite directions: one for numerals and the other for number words.

To explain the flat SNARC effects found in Israelis, there is no need to posit a conflict between reading text and reading numbers—nor is this explanation likely to be correct, given the absence of evidence that reading text shapes the MNL. Rather, the Israelis' data can be explained by a conflict between reading numerals and reading number words.[14] The CORE principle predicts the observed pattern of cross-cultural variation in the MNL solely on the basis of cross-cultural variation in written numbers: left-to-right SNARC effects for Westerners, right-to-left SNARC effects for Arabic speakers, and intermediate SNARC effects for Hebrew speakers (e.g., Shaki et al., 2009).

[13] In all four of the experiments showing reversed SNARC effects in Arabic speakers, some or all of the participants were from cultures in which numbers—both numerals and number words—are consistently written from right to left (Palestinians: Shaki et al., 2009; Palestinians and Israelis: Shaki et al., 2012; Lebanese: Zebian, 2005). Although Maier et al. (2015) do not specify what country in the Arabic-speaking world their participants were from, they say that their participants were "from a strictly right-to-left reading culture" and contrast it to cultures in which text and numbers are written in opposite directions. For simplicity, we use "Arabic-speakers" to refer to the people from the Arabic-speaking cultures in which both text and numerals are written from right to left.

[14] Some Arabic-speakers experience a similar conflict in the directions of written numbers and, accordingly, they show ambiguous space–number associations like some Israelis (Rashidi-Ranjbar, Goudarzvand, Jahangiri, Brugger, & Loetscher, 2014).

The MTL and MNL Are Shaped by Families of Experiences

Given the diversity of experiences that spatialize time, and the diversity of experiences that spatialize numbers, it is likely that no single artifact or practice can explain the direction of the MTL or the MNL. Rather there is a family of cultural artifacts and practices through which people experience space–time correlations (e.g., reading text, timelines), and another partly overlapping family of artifacts and practices through which people experience space–number correlations (e.g., finger counting, number lines). According to CORE, these families of experiences determine the directions of the MTL and of the MNL, within and across cultures. The influence of any individual artifact or practice on the MTL or the MNL should depend on its frequency or salience, and on the reliability with which it spatializes time or numbers.

Do the MTL and the MNL Interact?

Our results show a clear dissociation between the experiential determinants of the MTL and MNL. Are the MTL and MNL completely independent? In principle, space–time associations could interact with space–number associations to the extent that people *temporalize* numbers or *numberize* time. Yet, our data show no evidence that space–time and space–number mappings interact in people's minds.

Temporalizing numbers. Starting in childhood, people not only see numbers arrayed in space but also hear numbers listed in a consistent temporal order. When people count aloud, the word "one" is spoken before "two," and so forth. Given an MTL that progresses from left to right, the temporal sequence of number words in the count list could cause people to associate numbers that occur earlier in time with the left and numbers that occur later in time with the right, causing the MNL to conform to the MTL. Therefore, the MNL could be shaped both by experiential links between space and numbers (as in the act of finger counting) and, to the extent that people temporalize numbers, by the MTL. Reading and writing experience could, in principle, have an *indirect effect* on the MNL via the MTL.

However, the present results do not support this account. To the degree that the direction of the MNL depends on the direction of the MTL, changing the MTL should cause corresponding changes in the MNL. Yet, changing the MTL did not change the MNL in Experiment 1; participants showed standard space–number associations regardless of differences in their space–time associations. In Experiment 3, training changed both the MTL and MNL, but they changed in *opposite directions*. According to these findings, if the direction of the MTL has any influence on the MNL in adults, it is overwhelmed by the influence of space–number correlations in experience.

"Numberizing" time. In many cultures, when people communicate about exact points in time, they often use numbers (e.g., 12/31/2016, 10:30am). Earlier points in time are generally labeled with smaller numbers and later points in time with larger numbers (at least within a given cycle of 60 s, 12 hr, 31 days etc.) Given an MNL that increases from left to right, the numerical coding of temporal events could cause people to associate earlier events in time with smaller numbers and later events with larger numbers, causing the MTL to conform to the MNL. Therefore, the MTL could be shaped both by experiential links between space and time (as in the act of reading) and, to the extent that people numberize time, by the MNL.

However, the present results do not support this account. To the degree that the direction of the MTL depends on the direction of the MNL, changing the MNL should cause corresponding changes in the MTL. Yet, once again, the results of Experiment 3 show that the MNL and MTL changed in opposite directions. If the direction of the MNL has any influence on the MTL, it is overwhelmed by the influence of space–time correlations in experience.

In sum, although there are logically possible ways in which the MNL could "piggyback" on the MTL, or vice versa, the present data do not support any such relationship (at least not in the minds of adults; it remains possible that the MTL and MNL interact during the course of cognitive development). Experiment 1 shows a dissociation between the MTL and MNL, and Experiment 3 shows a double dissociation between the MTL and MNL. These mental metaphors have different experiential determinants, and appear to operate independent of each other.

The Hierarchical Structure of Mental Metaphors

How could a few minutes of reading or finger-counting change participants' implicit space–time or space–number mappings, overwhelming years of experience with their canonical mappings? The surprising flexibility of these mappings (e.g., Bächtold, Baumüller, & Brugger, 1998; Fischer et al., 2009) has led some researchers to doubt their centrality in our mental representations of time and number, especially in the case of the MNL (e.g., Fischer, 2006; Fischer et al., 2010; van Dijck & Fias, 2011). For example, van Dijck and Fias (2011, p. 114) noted that "the associations between numbers and space are more flexible than one would expect from a long-term memory representation." This flexibility, they argued, "might indicate that the spatial coding is not inherently associated to number but that it is constructed during task execution" (ibid). Likewise, Fischer (2006) suggests that "the future of the SNARC could be stark" (p. 1066), saying "it is possible that presence or absence of an association between numbers and space is the result of an individual's strategic decision in the light of both recent and current task demands, *and not a reflection of their mental representation of numbers*" (p. 1067, italics added). Does the flexibility of the MNL or the MTL challenge their existence, as these accounts suggest?

No. Here we argue that the flexibility of mental metaphors like the MTL and MNL is a predictable outcome of their hierarchical structure. According to Hierarchical Mental Metaphors Theory (HMMT; Casasanto & Bottini, 2014; Casasanto, 2017a), implicit associations between source and target domains can be characterized as a set of nested intuitive hypotheses (Goodman, 1955; Kemp, Perfors, & Tenenbaum, 2007). At the top of the hierarchy is the *overhypothesis*, which comprises a family of *specific hypotheses*. Overhypotheses are constructed on the basis of correlations between metaphorical source and target domains in the natural world (and may therefore be universal); specific hypotheses are conditioned by correlations between source and target domains people's linguistic, cultural, or bodily experiences, and are therefore language-specific, culture-specific, or body-specific (Casasanto, 2017a).

Hierarchical construction of the MTL. In the case of space and time, experience with the natural world could generate the overhypothesis *Progress through time corresponds to change in spatial position* (Casasanto & Bottini, 2014). The correlation between space and time is readily observable in moving objects: farther in space corresponds to later in time. This correlation obtains regardless of an object's direction of travel and therefore gives rise to an omnidirectional set of metaphorical mappings between time and space. Because this correlation obtains throughout the natural world, the overhypothesized mapping between space and time may be universal across cultures, either because it is innate or because it is learned from universal experiences.

As children begin to engage in cultural practices that, like reading, provide a correlation between space and time in a specific direction, they accrue a preponderance of evidence for one of the specific hypotheses within the overhypothesis. For example, reading and writing in English provides evidence for the specific hypothesis *Progress through time corresponds to* *rightward* *change in spatial position*, strengthening this specific hypothesis at the expense of its competitors and causing English speakers to use a rightward-directed MTL by default.

Importantly, strengthening the culturally preferred specific hypothesis does not cause its competitors to be lost: only weakened. Retaining all of the overhypothesized space–time mappings in long-term memory is what affords the flexibility we observe in these experiments: Participants in our training experiments were not learning a new space–time mapping, nor were they abolishing their usual mapping. Rather, when participants read or counted from right to left, this experience increased the weight of evidence for one of their overhypothesized (but culturally dispreferred) space–time mappings, strengthening it to the point that it influenced behavior and transiently weakening the culturally preferred mapping as a consequence. On this theory, people's mental metaphors linking progress through time with position in space can be fundamental to their conception of time but also remarkably flexible.

Hierarchical construction of the MNL. What regularities in experience might generate overhypotheses about space and number in the mind of a child? In counting objects, people assign different number words to objects in different spatial locations. These words follow a strict ordered sequence but objects can be counted along numerous spatial paths. On the basis of this experience, children could generate the overhypothesis, *Progress through numerical order corresponds to change in spatial position*. Exposure to culture-specific numerical practices (like finger counting) and artifacts (like written number lines) provides children in Western cultures with evidence for the specific hypothesis, *Progress through numerical order corresponds to* *rightward* *change in spatial position*. When children practice reading or writing a series of numbers (e.g., from 1 to 10), progress through the numbers corresponds to progress rightward across the blackboard or page. These experiences should increase the weight of evidence for a left-to-right MNL relative to alternative space–number mappings.

According to HMMT, finger counting in one direction or another in our experiments neither created new space–number mappings nor eliminated old ones. Rather, our right-to-left finger-counting training increased the weight of evidence for one of the culturally dispreferred specific mappings comprised by the overhypothesis, transiently strengthening the right-to-left mapping and weakening (but not extinguishing) participants' usual left-to-right mapping.[15] On this account, the flexibility of the MNL is not a symptom of psychological impotence—nor is it evidence that space–number mappings are not stored in long-term memory—rather, the representational flexibility of space–number metaphors is a product of their hierarchical structure.[16]

Can the Results Be Explained by a "Generalized Magnitude System?"

According to A Theory of Magnitude (ATOM; Walsh, 2003), spatial, temporal, and numerical magnitudes are "computed according to a common metric," constituting a *generalized magnitude system* (GMS) for representing mental magnitudes across conceptual domains (see also Srinivasan & Carey, 2010). Can the purported GMS explain the findings we report here? The present experiments were not designed as a test of the GMS proposal, but we note that our results are incompatible with the predictions that would follow from this proposal.

The GMS proposal is strictly concerned with mental magnitudes (e.g., temporal duration and numerical cardinality) but neither the MTL nor the MNL appears to be a mapping of magnitude, despite what many researchers assume (e.g., Fias, 1996). Rather, they seem to be mappings of temporal and numerical *order* (Casasanto & Bottini, 2014; Fitousi, Shaki, & Algom, 2009; Ginsburg, van Dijck, Previtali, Fias, & Gevers, 2014). This confusion between magnitude and order is common in the MTL and MNL literatures, in part because time and number have both magnitude and order; people can reason about temporal magnitude (i.e., how much time) or temporal succession (i.e., when in time), and they can reason about numerical magnitude (e.g., a set of five things) or numerical order (e.g., the fifth thing in a sequence). These different aspects of time and of number illustrate the critical distinction between *prothetic* domains (i.e., domains in which people can experience quantitative variation) and *metathetic* domains (i.e., domains in which people can only experience qualitative variation; Stevens, 1957). People *do* map prothetic aspects of time[17] and number[18] (i.e., duration and cardinality) onto space, but these mappings do

[15] The present study focused on applying the CORE principle to explain how cultural experiences shift the weight of evidence from one *specific hypothesis* to another. CORE may also apply to the construction of *overhypotheses*, assuming that they are based on observable source-target correlations in the natural world, no matter whether they are learned over developmental time or acquired over evolutionary time.

[16] Did our training experiences change representations in long-term memory (LTM)? Yes, the results of Experiments 2 and 3 can only be explained by changes in LTM, since participants were not finger counting during the test phase.

[17] In addition to spatializing temporal order (i.e., the MTL), people also spatialize temporal *magnitude*; they implicitly associate longer temporal durations with longer spatial extents. Like the MTL, this mapping between distance and duration can also be explained by the CORE principle; as objects travel further, more time passes. Thus, spatial and temporal magnitudes are positively correlated in people's experience. Therefore, according to CORE, spatial and temporal magnitudes should be positively related in the mind, as has been found in dozens of experiments (e.g., Cai, Wang, Shen, & Speekenbrink, 2018; Casasanto & Boroditsky, 2008; Srinivasan & Carey, 2010).

[18] In addition to spatializing numerical order (i.e., the MNL), people also spatialize numerical *magnitude*; they implicitly associate greater numerical cardinalities with greater spatial sizes and extents. Like the MNL, these mappings between numerical and spatial magnitude can also be explained by the CORE principle; sets of greater cardinality occupy more space. Thus, spatial and numerical magnitudes are positively correlated in people's experience. Therefore, according to CORE, spatial and numerical magnitudes should be positively related in the mind, as has been found in numerous experiments (e.g., de Hevia et al., 2014; van Dijck et al., 2015).

not constitute the MTL and MNL discussed in the present paper (and many others). Given that the MTL and MNL have metathetic source domains (i.e., spatial position, not length) and metathetic target domains (i.e., temporal and numerical order, not magnitude), the large literature on mental magnitudes is not of direct relevance to this study.

The confusion between magnitude and order may be especially pronounced in numerical domains because of a peculiar feature of numbers: Numbers are ordered according to their relative magnitudes. In principle, the MNL could be a mapping of numerical magnitude or order (or both), but many researchers have assumed that the SNARC effect arises from "the activation of number magnitude" (e.g., Nuerk et al., 2005, p. 192). Yet, this assumption is at odds with a variety of empirical findings. For example, reliable SNARC-like effects are found for stimuli that do not vary in magnitude; people spontaneously spatialize letters of the alphabet and novel sequences of fruits and vegetables, even though these stimuli do not vary in magnitude (e.g., "b" is not more than "a"; van Dijck & Fias, 2011; Gevers et al., 2003). Moreover, if numerical cardinality and ordinality are made to vary independently (by training participants on random number sequences), people spontaneously spatialize the numbers according to their ordinality, despite their cardinality (e.g., Ginsburg et al., 2014; van Dijck, Fias, & Andres, 2015). In sum, ordinality is sufficient to produce SNARC (and SNARC-like) effects, and ordinality has been shown to trump cardinality when these factors are pitted against each other in tests of spatial mappings. Therefore, there is no reason to posit that the MNL is a mapping of anything other than numerical order. (For this reason, the so-called "magnitude comparison task," which is one of the classic tests of the SNARC effect, may be a misnomer since it can be performed using ordinality, alone.) The same reasoning applies to the MTL; people reliably spatialize days of the week (Gevers, Reynvoet, & Fias, 2004) and months of the year (Experiments 1 and 3; Gevers et al., 2003) even though Tuesday is not *more* than Monday and February is not *more* than January. Therefore, both the MTL and MNL appear to be mappings of order, not magnitude.

Even if the MTL and the MNL were mappings between prothetic domains (i.e., length, duration, and cardinality), the present findings could not be explained by a GMS. At the heart of the GMS proposal is the idea that magnitudes in different domains—including time, number, and space—are "linked by a common metric" in the brain and mind (Walsh, 2003, p. 484). Therefore, on this proposal the relationship between space and time should not be dissociable from the relationship between space and number. On the contrary, if "time and number draw upon common magnitude mechanisms" (ibid, p. 484), then anything that changes space–time relationships should also change space–number relationships, in the same way.[19] Yet, here we repeatedly showed dissociations between space–time mappings and space–number mappings. Therefore, even if the MTL and MNL were mappings of temporal and numerical magnitude, the pattern of results we found here would provide evidence against a GMS.

Beyond Time and Number: The CORE Principle Explains Mappings in Other Domains

The present experiments provide strong support for the CORE principle, using the MTL and MNL as testbeds, and show how cultural experiences can shape mental metaphors. But the predictive power of CORE is not limited to these two mappings, nor to the domains of space, time, and number—nor to effects that are *culture-specific*. A brief examination of previous findings reveals that, on the contrary, the CORE principle can explain mental mappings in other conceptual domains, involving correlations that are *body-specific* or *language-specific*. For example, in addition to time and number, people also spatialize emotional valence, implicitly associating positive emotions with the right side of space and negative emotions with the left side, at least in right-handers. This lateral space-valence mapping reverses in left-handers, who implicitly associate positive emotions with the left side (Casasanto, 2009; Casasanto & Henetz, 2012). What causes people to spatialize emotional valence on the lateral axis at all, and what causes left- and right-handers to do so in systematically different ways? Casasanto and colleagues attribute these body-specific space-valence mappings to "correlations in bodily experience" (Casasanto, 2009, p. 360) that depend on handedness; whereas right-handed people tend to interact more fluently on the right side of space, left-handers tend to interact more fluently on the left. Given that more fluent experiences are more positive, different patterns of hand use provide different "correlations between emotional states and lateralized physical actions," and therefore, according to the CORE principle, should shape the way people map emotional valence onto lateral space. Indeed, changing the relative manual fluency of the two hands (by artificially handicapping one of them), transiently changes people's implicit space-valence mappings, consistent with CORE (Casasanto & Chrysikou, 2011). As this example illustrates, the CORE principle governs how correlations in experience shape mental representations whether those COREs are culture-specific (e.g., reading direction) or body-specific (e.g., handedness).

The CORE principle also applies to correlations in linguistic experience. For example, in languages like English, people talk about musical pitches as low or high, and this convention provides a correlation in language between pitch and vertical space. In some other languages, like Farsi, pitches are described as thick or thin, providing a correlation in linguistic experience between pitch and thickness (Shayan, Ozturk, & Sicoli, 2011). Do these correlations in linguistic experience shape the way people conceptualize pitch, even when they are not using language? A series of psychophysical experiments showed that they do (Dolscheid, Shayan, Majid, & Casasanto, 2013). When Dutch participants (who use height-pitch metaphors like English-speakers) were asked to sing back a tone they just heard, their pitch was influenced by irrelevant spatial information; seeing a horizontal line appear high on a computer screen caused them to sing at a higher pitch and seeing a lower line caused them to sing at a lower pitch. Whereas this irrelevant height

[19] A related account posits that associations between conceptual domains result from their "structural similarity" (Murphy, 1996; Srinivasan & Carey, 2010), but this proposal cannot explain the current pattern of results. In our experiments, space, time, and number share the same ordinal structure. Therefore, according to the structural similarity account, people should associate ordinality in space with ordinality in time and in number in the same way, regardless of the correlations between these domains in their experience; it should not have been possible to change space–number associations in one direction and space–time associations in the opposite direction given the same spatial training experience (as we found in Experiment 3).

information interfered with pitch reproduction in Dutch speakers, it had no such effect in Farsi speakers. Instead, Farsi participants' singing was affected by line *thickness*; Farsi participants sang back tones at higher pitches after seeing a thinner line and lower pitches after seeing a thicker line. And just as Farsi speakers could successfully ignore line height, Dutch participants could successfully ignore line thickness. When Dutch speakers were trained to talk about pitch as thick or thin (like Farsi speakers), they could no longer ignore line thickness; these language-trained Dutch participants sang higher pitches after seeing thinner lines and lower pitches after seeing thicker lines, like native Farsi speakers. These findings provide an example of how correlations in linguistic experience—in this case between space and pitch—determine which mental metaphors people use, just as the CORE principle predicts.

In sum, people experience correlations between many conceptual domains, well beyond the domains of space, time, and number (for review, see Casasanto, 2016). These correlations are provided not only by cultural experiences (like reading), but also by bodily experiences and linguistic experiences. Across multiple conceptual domains and types of experience, the CORE principle (and its parent theory HMMT) can be used to predict whether and how a given experience should shape metaphorical mappings between conceptual domains.

Conclusions

People use space to conceptualize abstract domains like time and number, perhaps universally, but the specifics of space–time and space–number mappings vary across cultures. This cross-cultural variation in both the MTL and MNL has long been attributed to reading, writing, and directional scanning experience. However, here we show that, in the case of the MNL, the data taken as evidence for the reading/writing/scanning hypothesis have been misinterpreted, for more than two decades. We then show that the CORE principle correctly predicts which aspects of cultural experience do—and do not—influence a given mapping. As predicted by CORE, the MTL was selectively shaped by aspects of experience that spatialize time, whereas the MNL was selectively shaped by aspects of experience that spatialize numbers. When a single experience spatialized time and numbers in opposite directions, this experience had opposite effects on participants' MTL and MNL. These findings show that the MTL and MNL have distinct experiential bases, and challenge the widespread claim that both of these mappings are shaped by reading/writing experience, directional scanning habits, or by all spatially oriented activities. Although the MTL and MNL do not depend on the same set of experiences, they are governed by the same principle: Abstract conceptual domains are spatialized in the mind according to the way they are spatialized in experience.

The predictive power of the CORE principle is not limited to the domains of space, time, and number, nor is it limited to cultural experiences like reading and finger counting. Rather, in principle, CORE can be used to predict whether, and how, any experience should affect metaphorical mappings between any two conceptual domains. Beyond the cultural experiences we tested here, experiences with language, with one's own body, and with the natural world all provide correlations that can create or change our mental metaphors. CORE provides a principled way to explore how diverse kinds of experience shape our mental representations of abstract concepts.

Context Paragraph

How is the diversity of human experience reflected in our brains and minds? Cultural differences in the conceptualization of time and number provide a rich testbed in which to explore this question. Time and number are universal fixtures of the natural world; what causes people from different cultures to conceptualize them differently? After decades of research on the cultural determinants of the mental timeline (MTL) and mental number line (MNL), the leading proposals have remained underspecified and poorly supported by empirical evidence. Reframing these space–time and space–number mappings as *mental metaphors* allowed us to develop a motivated theoretical account of the observed cross-cultural differences: the CORrelations in Experience (CORE) principle. A series of experimental interventions validated CORE and supported a central component of a larger theory of metaphorical mental representation, *hierarchical mental metaphors theory* (Casasanto & Bottini, 2014), which seeks to explain the structure and origins of some of our most fundamental abstract concepts.

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