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METAPHORICAL MAPPINGS OF TIME AND NUMBER:
HOW CULTURAL EXPERIENCE SHAPES COGNITIVE UNIVERSALS

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For Irene.

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ABSTRACT

How do people reason about things they cannot hear, see, or touch? In metaphorical mental representations, people understand abstract conceptual domains, like time and number, using knowledge of other domains, like space. The tendency to spatialize time and number may be a cognitive universal, but the specifics of these metaphorical mappings 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, here I propose and test a general principle, which I call the CORrelations in Experience (CORE) principle, according to which different aspects of experience should selectively affect different metaphorical mappings. Across three training experiments, I show that the MTL is shaped by experiences that provide a correlation between space and time, whereas the MNL is 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 assumption that both mappings are determined by a common set of cultural experiences. 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 map abstract domains in their minds according to the ways those domains are spatialized in their experience.

1. Introduction

People come to understand the world around them through their senses and the actions of their bodies. Yet, we think not only about the objects and events that compose our physical surroundings, but also about abstract ideas like freedom, democracy, and truth. How? How do people reason about things that they cannot see, hear, or touch? Here, I investigate this question using as testbeds two paradigm cases of abstract conceptual domains: time and number.

1.1 Spatial representations of time and number: clues from metaphorical language

How do people reason about abstract conceptual domains like time and number? The first clues come from the way people talk; when people talk about time or number, they often use spatial language. For example, people talk about "looking *forward*" to events in the future or reminisce about times "way *back*" in the past, describing points in time in terms of locations in sagittal (front-back) space. To describe the temporal duration of an event, people use terms for spatial length, as in "a *long* night" or "a *short* visit." Numbers can be "*big*" or "*small*," or they can be "*high*" or "*low*," but all of these terms are spatial terms applied to a non-spatial domain. What can these expressions in language tell us about the way people think? According to Lakoff & Johnson's Conceptual Metaphor Theory (1980 a, b, c), these metaphors in language reflect an underlying system of metaphorical mental representations in which "we conceptualize one mental domain in terms of another" (Lakoff, 1993, pp. 202).

Although Lakoff & Johnson made their argument "primarily on the basis of linguistic evidence" (Lakoff & Johnson, 1980a, pp. 454), behavioral evidence supports the proposal that these metaphors for time and number are more than just ways of talking – they are ways of thinking. For example, in one study, participants tended to lean forward more when thinking about the future and lean backward more when thinking about the past (Miles, Nind, & Macrae, 2010), consistent with linguistic expressions linking temporal order and sagittal space. In other studies, when participants saw stimuli that extended farther in space they mistakenly judged them to last for a greater duration, consistent with expressions linking length in space with “length” in time (Casasanto & Boroditsky, 2008; Gijssels & Casasanto, 2017, for a review).

Other studies have tested whether people think about numbers the way they talk about them. For example, when participants were asked to judge which of two digits was larger, in physical size or in numerical magnitude, their judgments were faster when physical and numerical size were congruent (e.g., a small number 4 beside a large number 8) than when they were incongruent (e.g., a large number 4 beside a small number 8; Pansky & Algom, 1999), consistent with metaphorical expressions linking size and number. Likewise, when participants classified centrally-presented numbers (as even or odd) by directing their gaze to one of two visual targets they were faster to make upward eye movements in response to “high” numbers and downward eye movements in response to “low" numbers, as suggested by expressions linking numbers with vertical space. In these examples, the behavioral evidence reflects patterns in metaphorical language, supporting Lakoff & Johnson’s proposal that metaphorical ways of talking reflect metaphorical ways of thinking. However, people also think metaphorically in ways that do not show up in language.

1.2 Spatial representations of time and number: Beyond language

Across cultures, people implicitly map both time and number onto the lateral (left-right) spatial axis, despite the absence of any corresponding linguistic expressions. Although one of the ways English-speakers think about time follows linguistic metaphors linking time with front-back space, we also think about temporal sequences using lateral space, forming a *mental timeline* (MTL) with earlier times on the left and later times on the right. Likewise, although one of the ways English-speakers think about number follows linguistic metaphors linking numbers with vertical space, we also think about numerical sequences using lateral space, forming a *mental number line* (MNL) with smaller numbers on the left and larger numbers on the right. These lateral space-time and space-number associations have been found in people's spontaneous gestures (Casasanto & Jasmin, 2012; Fischer, 2008; Shaki, Fischer, & Göbel, 2012), eye movements (Fischer, Castel, Dodd & Pratt, 2003; Loestscher, Bockisch & Brugger, 2008), and patterns of reaction times (Dehaene, Bossini, & Giraux, 1993; Wood, Willems, Nuerk & Fischer, 2008; Shaki, Fischer, & Petrusic, 2009), even though both are entirely absent from spoken and written language (Evans, 2003).[1] In English, a meeting can move "forward" or "backward" in time, but not "leftward" or "rightward." Likewise, numbers can go "up" or "down" but not "left" or "right."

Can the MTL and MNL be considered metaphorical mental representations, despite their absence from language? Yes. According to Lakoff, "the locus of metaphor is not in language at all, but in the way we conceptualize one mental domain in terms of another" (1993, p. 202). Therefore, "not all conceptual metaphors are manifested in the words of a language" (Lakoff & Johnson, 1999, p. 59). Reasoning clearly about this dissociation between metaphors in language and metaphors in thinking requires a new set of terms. I will abandon the term "conceptual metaphor," which has been used ambiguously (e.g. "Conceptual metaphor is pervasive in both thought and language"; Lakoff & Johnson, 1999, p. 50). Instead, following Casasanto (2017b), I will distinguish *linguistic*

[1] In the only known exception, members in the US Military use linguistic metaphors linking temporal sequence with lateral space. For example, in that context, a meeting that has been "shifted right" has been rescheduled to an earlier time and a meeting "shifted left" will occur later (Casasanto & Jasmin, 2012).

metaphors, which describe patterns of metaphorical language, from *mental metaphors,* which describe patterns in metaphorical thinking.

What does it mean to think metaphorically? In a mental metaphor, people construct an implicit point-to-point mapping between wo conceptual domains; a source domain (e.g. space) and a target domain (e.g. time or number), which is typically more abstract (Casasanto, 2010; Lakoff & Johnson, 1980c). By importing structure from the source domain into the target domain, mental metaphors facilitate inferences in the target domain. In the case of the MTL or MNL, changes in temporal or numerical sequence are conceptualized metaphorically as changes in lateral spatial position. These spatial mappings may be fundamental to the way people conceptualize time and number (e.g. Hamdan & Gunderson, 2017), and yet they have been largely neglected by metaphor theorists. Why? By looking to language for signs of metaphorical thinking, many metaphor theorists have had blind spots in the study of metaphoric mental representation, neglecting mental metaphors like the MTL and MNL that, however pervasive or important, remain unspoken (see Casasanto, 2017a for discussion).

1.3 Where do the MTL and MNL come from?

According to Conceptual Metaphor Theory, each of our basic metaphors “arises naturally, automatically, and unconsciously through everyday experience” (Lakoff & Johnson, 1999, p. 51; but see Casasanto, 2013). For example, the mental metaphor linking time with front-back space could be based in the experience of locomotion; as people walk along a path, the objects and events that they will experience in the future lie ahead of them in space whereas those they have already experienced lie behind them (de la Fuente, Santiago, Román, Dumitrache, & Casasanto, 2014). Likewise, the implicit association between number with vertical height may be based on experiences in which piles of objects grow taller as more objects are added. This relationship between number of objects and height obtains throughout the natural world (Lakoff & Johnson, 1980c). According to Lakoff & Johnson (1999, p. 51), these "[u]niversal early experiences lead to…universal (or widespread) conventional conceptual metaphors." Therefore, mental metaphors "are universals that are not innate," but rather are learned from experience with the natural world.

If mental metaphors arise from experience with the natural world, then people could develop a common set of mental metaphors "from our earliest years" (Lakoff & Johnson, 1999, p. 51). Consistent with this proposal, recent evidence suggests that *some* space-time and space-number metaphors may be present in pre-linguistic infants, even in the first few hours after birth. Specifically, infants associated greater temporal and numerical magnitude with greater spatial magnitude (Bulf, de Hevia, & Macchi-Cassia, 2015; de Hevia & Spelke, 2010; Srinivasan & Carey, 2010; Lourenco & Longo, 2010).[2] These findings support the proposal that these space-time and space-number associations are "cognitive universal[s]" (Tversky, Kugelmass, & Winter, 1991, p. 517; Göbel, Shaki, & Fischer, 2011, p. 546), which may arise from universal experience with the natural world.

Yet, the universality of space-time and space-number metaphors is challenged by the MTL and MNL, for two reasons. First, these mappings of time and number have no plausible experiential basis in the natural world. People do not systematically experience earlier events on one side of space and later events on the other; whereas the things we will experience in the future tend to lie

[2] In addition to the evidence for early links between numerical and spatial magnitude, some studies have been interpreted as showing a lateral MNL in neonates (de Hevia, Izard, Coubart, Spelke, & Streri, 2014) and even non-human animals (Rugani, Regolin, & Vallortigara, 2007; for review, see Rugani & de Hevia, 2016). These studies are open to an alternative interpretation, however: Hemispheric specialization for emotion predicts the same behavior in newborns and nonhumans, even if they have no MNL (Vallortigara, 2017).

in front of us, they do not tend to lie systematically to the right or left, at least not in the natural world. According to Radden (2004, p. 228), "the lateral axis with a left-right orientation…does not seem to offer any sensible spatial basis for our understanding of time at all." Likewise, people do not typically experience smaller numbers of objects on the left and larger numbers of objects on the right. Why not? Objects in the natural world are not systematically arranged in numerical order, and even if they were, the direction in which they increased in left-right space would depend critically on the orientation of the observer's body; simply turning around would reverse any incidental left-right spatialization of number. In principle, our own bodies could spatialize numbers on the left-right axis (e.g. if we had more fingers on the left hand than on the right hand), but as Clark (1973) noted, whereas human bodies are asymmetric on the front-back axis and the up-down axis, they have "one natural plane of symmetry, the vertical plane separating left and right" (p. 33). Yet, despite the absence of any reliable experimental bases in the natural world, people reliably associate both time and numbers with lateral space.

Second, these space-time and space-number mappings are dramatically different across cultures. Whereas Western adults tend to show MTLs and MNLs that go from left to right (Dehaene, Bossini, & Giraux, 1993; Wood, Willems, Nuerk, & Fischer, 2008; Bonato, Zorzi & Umiltà, 2012), adults in some other cultures spatialize time and numbers in the opposite direction, from right to left (e.g. Fuhrman & Boroditsky, 2010; Shaki, Fischer, & Petrusic, 2009). This culture-specificity has also been shown in young children, both for mappings of time (Bottini & Casasanto, 2013; Casasanto, Fotakopoulou, & Boroditsky, 2010) and number (Hoffmann, Hornung, Martin, & Schiltz, 2013; Opfer, Thompson, & Furlong, 2010; Shaki et al., 2012). These well-established cultural effects challenge the idea that mental metaphors for time and number are universally shared. Rather, mental metaphors like the MTL and MNL are "culturally mediated" (Bonato, Zorzi, & Umlità, 2012, p. 2258), but the principles that govern this cultural variation remain unclear.

In this thesis, I present three studies designed to determine how culture shapes the MTL and MNL. Are the MTL and MNL shaped by the same or different experiences? What determines how a given experience will shape a given mapping in the mind? Rather than observing cross-cultural correlations, these experiments manipulate the space-time and space-number relationships in participants' experience, in order to test for causal relationships between culture and cognition. I propose and test a general principle by which different aspects of experience affect different mental metaphors: the CORrelations in Experience (CORE) principle. By investigating how members of different cultures come to think differently, this research seeks to clarify cognitive processes that may be common to all human minds.

2. Background and Motivation

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 on some level, 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). In English-speaking 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, English speakers 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; Loestscher, 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 (Dehaene, Bossini, & Giraux, 1993; Wood, Willems, Nuerk & Fischer, 2008; Bonato, Zorzi & Umiltà, 2012), at least in Western cultures. By contrast, people in some other cultures show the opposite set of associations, indexing MTLs and 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.

How does 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 are determined by the direction in which people read and write text. Yet, as we will argue, the evidence for this assumption is well supported for the MTL but not for the MNL. Here we propose that the MTL and MNL have different experiential bases and that, like other spatial mappings in people's minds, each mapping is shaped by a distinct set of cross-domain correlations that are observable in the world. Some previous proposals have suggested that many culture-specific experiences, not limited to reading and writing, may determine the direction of the MTL and MNL, but it has remained unclear which experiences influence which spatial mappings, and why. We introduce the CORrelations in Experience (CORE) principle, according to which people spatialize abstract domains in their minds the way these domains are spatialized in the world. The CORE principle allows us to predict *a priori* which kinds of experiences should – and should not – influence the spatial mapping of any abstract domain, including time and number. Consistent with CORE, we show that the MTL is selectively shaped by experiences that spatialize time, whereas the MNL is selectively shaped by experiences that spatialize number.

2.1 Does Reading Experience Shape the MTL?

People from Western cultures show MTLs that progress from left to right (Spaniards: Santiago, Lupáñez, Pérez, & Funes, 2007; Canadians: Weger & Pratt, 2008), whereas people from cultures where text is written from right to left 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). Despite this clear correlation, these findings do not indicate whether the direction of reading and writing is a cause or an effect of cross-cultural variation in implicit space–time mappings, in part because cultural practices tend to covary. Groups who write from left to right also tend to spatialize time on calendars and graphs from left to right (Tversky et al., 1991), and to gesture according to a left-to-right mental timeline (Casasanto & Jasmin, 2012; Cooperrider & Nuñez, 2009). This covariation among cultural practices leaves open many possible scenarios according to which orthography could play a primary causal role, a mediating role, or no causal role at all in determining the direction of the MTL (see Casasanto & Bottini, 2014).

Testing whether reading experience can play a causal role in determining the direction of the MTL (or any other spatial mapping) requires experimental intervention. Casasanto and Bottini (2014) intervened on reading experience by randomly assigning 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 Hebrew speakers. These data show that, beyond correlating with the direction of the MTL across cultures, reading experience can play a causal role in determining the direction of the MTL.

2.2 Does Reading Experience Shape the MNL?

The role of reading experience in determining the direction of the MNL is much less clear. Although it is widely assumed that the direction of the MNL covaries with the direction of written text across cultures, there is little evidence to support this assumption. In general, 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 (Deheane et al, 1993, Experiment 7).[3] 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 (Fischer & Shaki, 2016; Zohar-Shai, Tzelgov, Karni, & Rubinsten, 2017).

Another study (Zebian, 2005) has often been cited as evidence that reading experience determines 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 the Arabic monolinguals than in Arabic-English bilinguals who had daily exposure to Western writing systems, contrary to predictions based on reading experience. Second, English monolinguals showed no significant SNARC effect, also contrary to predictions (and to dozens of other findings). Therefore, neither the observed reversal of the SNARC effect nor the absence of a reliable SNARC effect in a group of illiterate participants has any clear interpretation (see Shaki et al., 2009 for a similar critique of these data).

[3] 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 Fisher, Mills, & Shaki, 2010).

The clearest demonstration to date of a reversed SNARC effect was found among Arabic-speaking Palestinians (Shaki et al., 2009). However, 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 this body of studies 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? 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 randomly 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 (also see 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 was responsible for the Russian-Hebrew differences. In order 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 (Deheane 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" (Deheane et al., 1993, pg. 394). This claim, which we call the *reading/writing hypothesis*, has influenced a generation of researchers seeking to explain the origins of the MNL, who have concluded that reading/writing plays a "fundamental" (Rugani & de Hevia, 2017), "crucial" (Bonato et al., 2012, p. 2270), and "pronounced" (Patro, Nuerk, & Cress, 2016, p. 4) role in determining the direction of the MNL. As one paper states, "The effect of reading/writing direction in affecting the spatial-numerical association has been shown unambiguously" (Rugani & de Hevia, 2017, p. 364).

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; Shaki & Fisher, 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.

2.3 Extensions of the reading/writing hypothesis

Although the reading/writing hypothesis remains widely accepted (e.g., for a review see Rugani & de Hevia, 2017), it has been modified over the past two decades in light of new findings. Several studies have found 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 et al., 2012). To accommodate such findings, some researchers have attributed the direction of the MNL not only to "reading and writing" (Zebian, 2005) but more generally to "spatially directional scanning of visual materials" (Shaki & Fischer, 2008, p. 596; see also Fischer, 2012; Patro, Fischer, Nuerk, & Cress, 2016), turning the reading/writing hypothesis into a reading/writing/scanning hypothesis.

In other proposals, the set of experiences proposed to shape the MNL has been further expanded to include "all experienced actions and events oriented in space" (Patro, Nuerk, & Cress, 2016, p. 4). For example, Fischer, Mills, & Shaki (2010) suggested that the MNL could depend on "any number of uncontrolled factors, such as finger counting habits…experiences with rulers or time lines…cultural factors…and even multi-digit numbers themselves" (p. 335). Likewise, according to the *spatial experience hypothesis* (Göbel, Shaki, & Fischer, 2011), "spatial experiences…lead to cross-cultural differences in the spatial representation of numbers" (p. 560); the authors mention reading, finger counting, number lines, and arithmetic operations as being potentially relevant.

Although the reading/writing/scanning and spatial experience hypotheses do not posit a mechanism by which these spatial experiences should influence the MNL, the *quantitative summation hypothesis* (Patro, Nuerk, & Cress, 2016) suggests that "experiencing spatially organized sequences of movement might activate in the brain the process of *quantitative summation*" (p. 3, italics added), in which people implicitly track increases in spatial, temporal, and numerical magnitude. This process of "adding up magnitudes…might enhance conceptual associations between magnitudes and left/right directions" (p. ibid.)

Rather than rejecting the role of reading/writing in shaping the MNL, the reading/writing/scanning, spatial experience, and quantitative summation hypotheses propose 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, Nuerk, & Cress, 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, all of these proposals predict that reading and writing should be among the experiences that shape the MNL, and are therefore challenged by the studies reviewed above that fail to support – or directly contradict – the reading/writing hypothesis. According to the principle we propose below, reading and writing experience should not play a causal role in determining the direction of the MNL.

2.4 Different mappings depend on different experiences: The CORE principle

Why might reading experience determine the direction of the MTL but not the MNL? 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, 1980b). 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 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 principle, which we call the CORrelations in Experience principle (henceforth CORE), makes clear predictions about which aspects of experience should shape a given mental metaphor – and which aspects of experience should not. Specifically, according 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 number. Therefore, to evaluate whether reading/writing experience *should* influence the direction of the MTL and of the MNL, we consider whether reading/writing experience provides a correlation between space and time, and between space and number.

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, progresses gradually rightward "through" both space and time, and ends on the right side of the page at a later time. This relationship between space and time is an unavoidable feature of reading and is reinforced on every line of text: Progress through time correlates with progress rightward through space. The opposite relationship holds in reading Arabic or Hebrew text: Progress through time correlates with progress leftward through space (Casasanto & Bottini, 2014).

By contrast, the act of reading text provides no clear space-number correlation. Moving rightward across the page corresponds inevitably to progress along a temporal continuum, but not to progress along a numerical continuum (unless people were to enumerate words as they read them, which is unlikely, especially in light of documented interference effects between counting and language use; e.g., Frank, Fedorenko, Lai, Saxe, & Gibson, 2012). Likewise, 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 number. Therefore, on the basis of the CORE principle, reading 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.

Here we tested this proposal in three experiments. In Experiment 1, we tested whether reading experience (which provides a correlation between space and time) shapes both the MTL and MNL, or only the MTL. We trained participants to read English text either normally (from left to right) or mirror-reversed (from right to left). In Experiment 2, we tested whether finger counting experience (which provides a correlation between space and number) influences the MNL by training participants to count on their fingers in one direction or the other. Finally, in Experiment 3, we used a variation on our finger-counting protocol to test whether a single experience could have opposite effects on the MTL and MNL, by independently varying the space-time and space-number correlations that participants experienced.

The CORE principle makes distinct predictions from the reading/writing/scanning hypothesis, the spatial experience hypothesis, and the quantitative summation hypothesis with regard to the effects of reading and finger-counting experience on the MTL and MNL. Only CORE predicts that reading experience should affect the direction of the MTL but not the MNL. Likewise, only CORE predicts that, when finger-counting patterns are manipulated to spatialize time and number orthogonally, the same finger-counting experience should have 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.

3. 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. [4] 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. We reasoned that 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).

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[4] An earlier version of this chapter was published as:
Pitt, B., & Casasanto, D. (2016). Reading experience shapes the mental timeline but not the mental number line. In A. Papafragou, D. Grodner, D. Mirman, & J. Trueswell (Eds.), *Proceedings of the 38th Annual Conference of the Cognitive Science Society* (pp. 2753-2758). Austin, TX: Cognitive Science Society.

3.1 Method

Participants. Sixty-four right-handed native English speakers from the University of Chicago community participated for payment or course credit. Half 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-inch 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 minutes in the standard condition and 36 minutes in the reversed condition and was limited to 45 minutes 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, 3-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.

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 parity judgments (odd vs. even) are.

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.

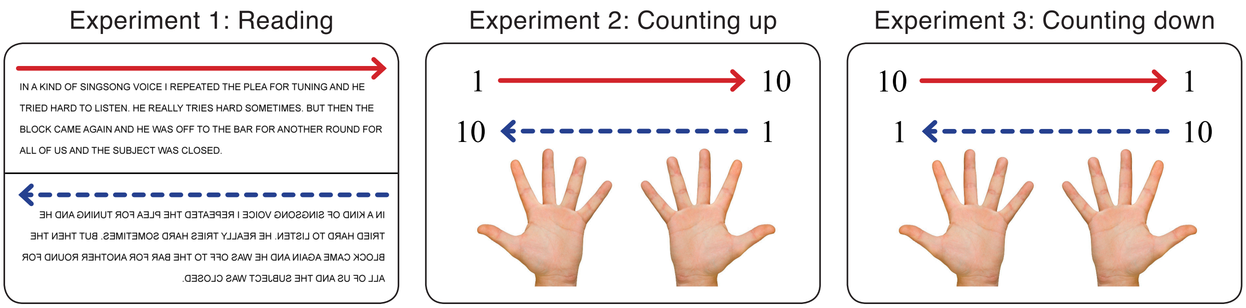

Figure 1. Training procedures for the three experiments. In Experiment 1 (left panel), participants read an English text in either standard orthography (solid red line) or mirror-reversed orthography (dashed blue line). In Experiment 2 (center panel), participants counted up to ten either rightward (solid red line) or leftward (dotted blue line). In Experiment 3 (right panel), participants either counted down-to-the-right (solid red line) or down-to-the-left (dashed blue line).

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 the participant to raise the hand corresponding to each of the responses to ensure s/he 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 1000 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).

3.2 Results

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%. The error rate did not differ significantly across reading conditions (standard = 3.20% +/- 0.16; reversed = 4.16% +/- 0.18; $\chi^2(1) = 2.10$, p = .15) or tasks (digits = 3.64% +/- .21; number words = 3.28% +/- .20; months = 4.11% +/- .22; $\chi^2(1) = 5.41$, p = .07). Inaccurate trials (3.68% +/- 0.12) were excluded from the RT analyses, as were accurate trials with RTs slower than 2000ms (4.78%).

RT Analyses. To evaluate space-time and space-number congruity effects, months were coded for ordinal position in the calendar year (i.e. Feb = 2, Oct = 10). 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 indexed by a significant interaction between response hand and ordinal position.[5] 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).

Space-Time Associations. RTs greater than 2.5 standard deviations from subject means were removed (3.28%), following Shaki & Fischer (2008). RTs were then log transformed to approximate a normal distribution of residuals. In the standard reading condition, participants

[5] For comparison with other findings, we also report and plot the SNARC effect in each task as a regression slope, following Fias (1996), regressing 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 (3-way and 4-way) interactions on which our experimental questions depend.

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 = -15.36ms/position). The space-time congruity effect in the reversed reading condition trended in the same direction but was only marginally significant ($\chi2(1) = 2.62$, p = .10; slope = -7.91ms/position). Of primary interest, the space-time congruity effect was significantly weaker in the reversed reading condition than in the standard reading condition ($\chi2(1) = 5.83$, 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 our chances of detecting an effect of reading training on the MNL.

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 = -7.61ms/position). Participants in the reversed reading condition also showed a significant standard SNARC effect ($\chi^2(1) = 12.06$, p = .0005; slope = -9.71ms/position). 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 = -6.03ms/position). Participants also showed a significant standard SNARC effect in the reversed reading condition ($\chi^2(1) = 6.44$, $p = .01$; slope = -3.18ms/position). 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.

Number tasks combined. In the standard reading condition, participants showed a significant SNARC effect ($\chi^2(1) = 6.67$, $p = .01$; slope = -6.88ms/digit). Participants in the reversed reading condition also showed a significant standard SNARC effect ($\chi^2(1) = 16.84$, $p = .0004$; slope = -6.52ms/position). 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 ($\chi^2(1) = 6.84$, $p = .009$), confirming that reading experience had different effects on the MTL and the MNL.

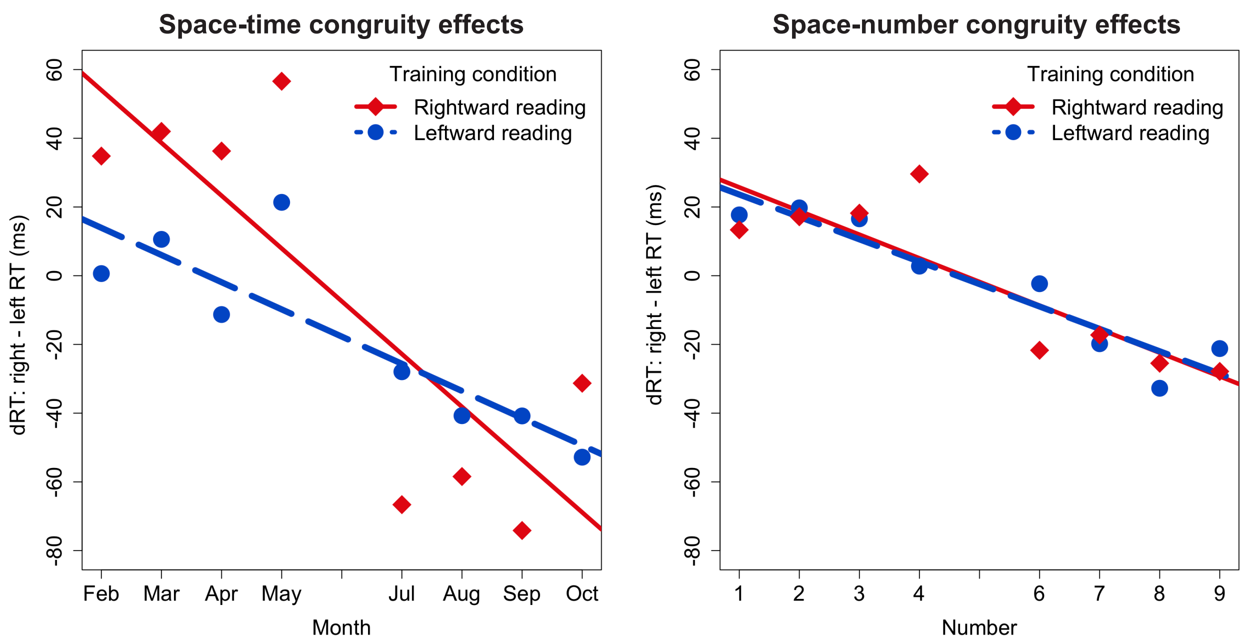

Figure 2. Results of Experiment 1. Left: The space-time congruity effects differed across reading conditions. Right: The space-number congruity effects did not differ across reading conditions; both conditions showed a standard SNARC effect.

3.3 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 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 claim that reading direction influences the MNL. Since the reading/writing/scanning, spatial experience (Göbel et al., 2011), and quantitative summation (Patro, Nuerk, & Cress, 2016) hypotheses all predicted that reading experience should affect the MNL, these data are consistent with only one of the theories we contrasted: CORE.

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 effect could have resulted from an insufficient experimental manipulation. 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 space-time congruity effects. Still, reading training had no discernable effect on the MNL.

If reading does not shape the direction of the MNL, then what kind experience does? According to the CORE principle, the MNL should be shaped by experiences that provide a correlation between space and number. 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.

4. 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 an explicit correlation between numbers and space; during finger counting, different numbers are associated with different fingers, each with a unique position in left-right space. For people whose finger-counting routines start with the left hand (habitual left-starters), small numbers are counted on the left side and large numbers are counted on the right side, and the opposite is true for right-starters. Can finger counting, as one example of an experience that spatializes numbers, affect the direction of the MNL? [6]

Correlational evidence suggests that it can. Left-starters were found to be more likely than right-starters to show a standard SNARC effect, even in the same culture (Fischer, 2008). Across cultures, finger-counting habits appear to covary with writing direction. Reportedly, Americans and western Europeans tend to be left-starters, whereas Persian-speaking Iranians tend to be right-starters (Lindemann, Alipour, & Fischer, 2011; but see Di Luca, Granà, Semenza, Seron, & Pesenti, 2006; Sato, Cattaneo, Rizzolatti, & Gallese, 2007; Sato & Lalain, 2008). These findings suggest that differences in finger counting could, in principle, contribute to observed cross-cultural variation in the MNL. Yet, on the basis of this correlational evidence, it is not possible to determine whether culture-specific finger-counting habits are a cause or an effect of culture-specific mental number lines.

Although there are many culture-specific practices and artifacts that spatialize number (e.g. rulers, calendars, written number lines), finger-counting practices may be especially effective in

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[6] An earlier version of this chapter was published as:
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shaping the MNL. A variety of studies have revealed tight links between fingers and numbers using purely behavioral tests (Badets, Pesenti, & Olivier, 2010; DiLuca et al., 2006; Di Luca & Pesenti, 2011; Domahs, Krinzinger, & Willmes 2008; Domahs, Moeller, Huber, Willmes, & Nuerk, 2010; Fayol, Barrouillet, & Marinthe, 1998; Gracia-Bafallu & Noël, 2008; Noël, 2005; Riello & Rusconi, 2011; Sixtus, Lindemann, & Fischer, 2018; Sixtus, Fischer, & Lindemann, 2017), neurostimulation (Rusconi, Walsh, & Butterworth, 2005; Sato et al., 2007), and brain imaging (Andres, 2015; Andres, Michaux, & Pesenti, 2012; c.f. Andres, Seron, & Olivier, 2007). Taken together, these findings have motivated "manumerical" accounts of numerical cognition, which posit a critical functional role for the fingers in the representation and manipulation of numbers (Fischer & Brugger, 2011; Wood & Fischer, 2008; see also Di Luca & Pesenti, 2011; Rinaldi, Di Luca, Henik, & Girelli, 2016).

In sum, there are at least three reasons to posit that finger counting should affect the MNL: (a) finger counting provides a correlation between numbers and lateral space, and should therefore influence the MNL according to the CORE principle; (b) finger counting patterns correlate (at least roughly) with the direction of SNARC effects observed within and across cultures; (c) the fingers are thought to play a privileged role in numerical representations. Yet, to date there has been no experimental test of a causal relationship between finger counting and the direction of the MNL.

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. 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. 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.

4.1 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 aloud on their fingers from 1 to 10, as they normally would. 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 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 on 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 minutes 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 a 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 500ms, 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.

4.2 Results

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, $p = 1$).

Accuracy. Overall, accuracy was above 96%. The error rate did not differ significantly between the rightward counting condition (4.08% +/- 0.20) and the leftward counting condition (3.89% +/- 0.19%; $\chi^2(1) = .24$, $p = .62$). The error rate in the parity judgment task (4.51% +/- .21) was significantly higher than in the magnitude judgment task (3.46% +/- .19; $\chi^2(1) = 6.48$, $p = .01$), but this difference was very small (about 1%). Inaccurate trials (3.99% +/- 0.14) were excluded from the RT analyses, as were accurate trials with RTs slower than 2000ms (0.93%).

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).

Parity task. RTs greater than 2.5 standard deviations 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 = -11.81ms/position). Although participants in the leftward counting condition also showed a significant standard SNARC effect ($\chi^2(1) = 4.96$, $p = .02$; slope = -4.98ms/position), 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 standard deviations 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 = -16.61ms/position). Although participants in the leftward counting condition also showed a significant standard SNARC effect ($\chi^2(1) = 5.32$, $p=.02$; slope = -7.62ms/position), 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.

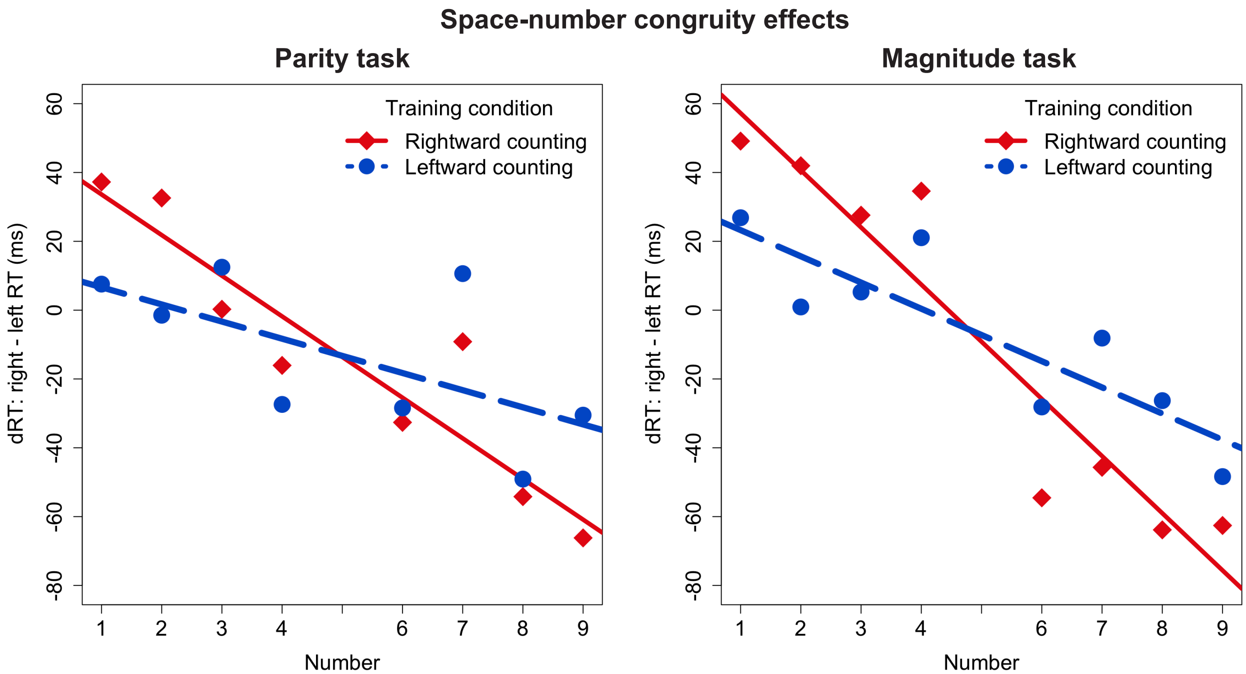

Figure 3. Results of Experiment 2. In both the parity task (left) and magnitude task (right), participants showed significant standard space-number congruity (SNARC) effects after counting rightward (solid red lines). These effects were significantly reduced after counting leftward (dashed blue lines).

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.

4.3 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 can play a causal role in shaping the MNL.[7]

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. However, not only is this skeptical account difficult to motivate theoretically, it is also inconsistent with the results of Experiment 2 (see also Fischer, Mills, & Shaki, 2010). Right-to-left reading training lasted about 36 minutes on average, whereas right-to-left finger counting only lasted about 25 minutes; 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 number (found in finger counting).

These results support the CORE principle, according to which finger counting (an experience that spatializes number) should affect the MNL. Yet, these results are consistent with other

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

accounts of the MNL as well. Insofar as finger counting is a “spatially oriented activit[y]” (Patro, Nuerk, & Cress, 2016, p. 4), the spatial experience and quantitative summation hypotheses also predict that finger-counting experience 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.

5. Experiment 3: The MTL and MNL are shaped by different aspects of experience

Together, the results of Experiments 1 and 2 rule out a strict interpretation of the reading/writing hypothesis, indicating that the direction of written text influences the MTL, but does not influence the MNL. Since the reading/writing/scanning (Shaki & Fischer, 2008), spatial experience (Göbel et al., 2011), and quantitative summation (Patro, Nuerk, & Cress, 2016) hypotheses all predict that reading direction *should* influence the MNL, evidence that rules out the reading/writing hypothesis also counts strongly against these other three hypotheses, and supports CORE. 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. [8]

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; fig. 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. 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

[8] A version of this chapter to appear in:
Pitt, B. & Casasanto, D. (2018). *Time and numbers on the fingers: Dissociating the mental timeline and mental number line.* Paper to be presented at the 40th Annual Conference of the Cognitive Science Society, Madison, WI.

on the fingers allowed me 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 hypotheses.

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 (counting down to the left, counting down to the right) 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.

Together, the reading/writing/scanning, spatial experience, and quantitative summation hypotheses make a distinct prediction from CORE. If "all spatially oriented activities" (Patro, Nuerk, & Cress, 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, these alternative hypotheses predict that training should change the MTL and MNL in the *same direction* whereas 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).

5.1 Method

Participants. 128 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. In order to avoid any effects of reading, all instructions and stimuli were pre-recorded 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 ten 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 ten 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 minutes 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 ten (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 twelve times, composing 192 trials per task. Participants were told to respond "as quickly and accurately as possible" and each trial ended automatically with an auditory alert if no response was given within 1.5 seconds after stimulus onset. The order of response mappings was crossed with the order of tasks and counterbalanced across participants.[9]

[9] As in Experiment 1, participants in Experiment 3 performed both the time task and the number task and the order of tasks was counterbalanced across participants and crossed with training

5.2 Results

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%. The error rate in the counting-down-to-the-right condition (4.68% +/- .13) was marginally lower than in the counting-down-to-the-left condition (5.66% +/- .15; $\chi^2(1) = 2.91$, p=.09). The error rate in the Time task (6.34% +/- .16) was significantly higher than in the Number task (4.00% +/- .13; $\chi^2(1) = 53.32$, 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 standard deviations from subject means were removed (2.18% 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-

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condition. However, in Experiment 3 we found that the effect of training differed significantly as a function of task order ($\chi^2(1) = 9.56$, p = .002). This order effect was driven by the Time task; the effect of training on the Time task depended on whether participants performed the Time task before or after the Number task ($\chi^2(1) = 5.92$, p = .01). To avoid this effect of task order, we adopted a design in which task varied between subjects, by analysing the data from subjects' first task only and doubling the sample (from 64 to 128 subjects).

right condition (10→1), in which participants started on the left and ended on the right, the space-time congruity effect was significant ($\chi^2(1)=8.93$, $p=.003$), indicating a reliable standard MTL (slope=-8.39ms/position). In the counting-down-to-the-left condition, the space-time congruity effect did not differ significantly from zero (1←10; $\chi^2(1)=0.71$, $p=.40$; slope=-2.37 ms/position). 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; $\chi^2(1)=8.78$, $p=.003$; 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.

Space-Number Associations. RTs greater than 2.5 standard deviations from subject means were removed (2.06% 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 ($\chi^2(1)=17.43$, $p=.0003$; slope=-11.65 ms/position), 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 ($\chi^2(1)=6.69$, $p=.01$; slope=-6.95ms/position). 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; $\chi^2(1)=11.71$, $p=.0006$; 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.

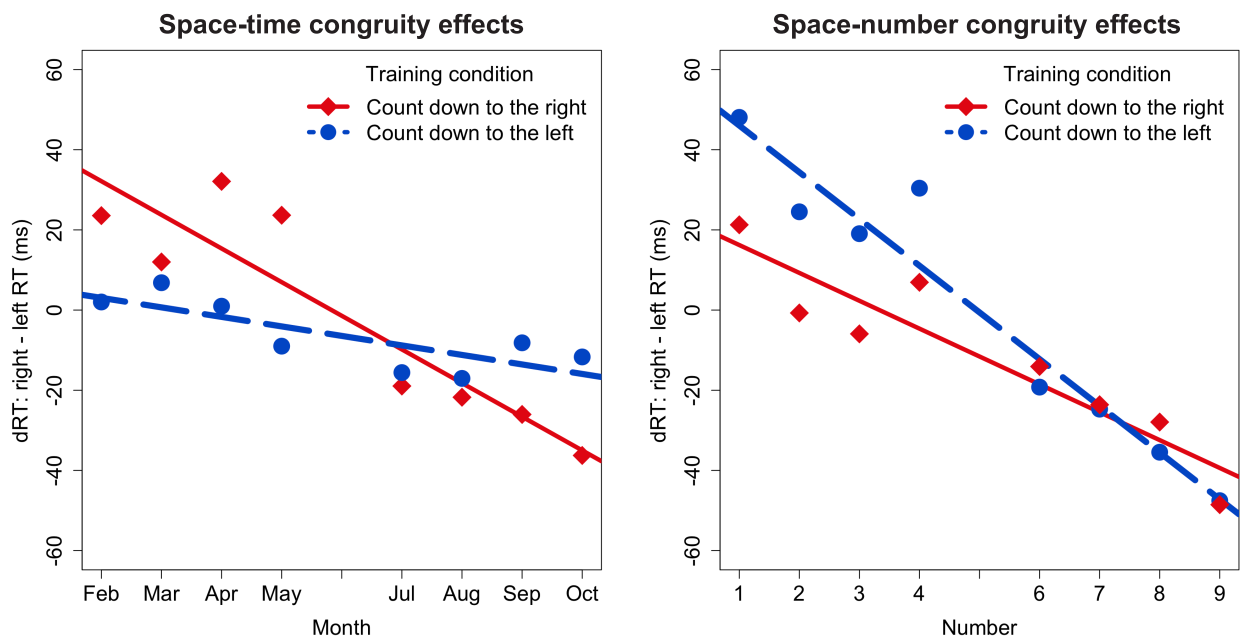

Figure 4. Results of Experiment 3, in which finger-counting training had opposite effects on the MTL and MNL. Left: In the time task, participants showed a significant standard space-time congruity effects after counting down to the right (solid, red line) and a significantly reduced effect after counting 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).

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 ($\chi^2(1)=18.79$, p=.0001). The finger counting training changed the MNL and MTL in opposite directions, as predicted by the CORE principle.[10]

[10] Training also had significantly different effects on the space-time and space-number effects when task was treated as a within-subject variable ($\chi^2(1) = 27.55$, p < .0001), suggesting that training independently changed the MNL and MTL *in the same participants*.

5.3 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. As predicted, 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 all previous attempts to explain the direction of the MNL, which posit that the MNL should follow the direction of scanning or moving through left-right space; here, the MNL followed the spatialization of numbers, despite the direction of scanning and moving across the fingers.

6. 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 differed according to the direction in which finger counting spatialized time, whereas space-number associations differed 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.

6.1 Reassessing the reading/writing hypothesis and its extensions

Our findings are incompatible with all of the proposals that have been advanced previously to explain the direction of the MNL (i.e., the reading/writing hypothesis and its extensions: the reading/writing/scanning, spatial experience, and quantitative summation hypotheses). Experiment 1 challenges all of these proposals because they all include reading in the set of experiences that should shape the MNL. The non-effect of reading training 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, Nuerk, & Cress, 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.

6.2 How CORE explains cross-cultural variation in the MNL

Beyond predicting the pattern of data found in the present study, CORE can also explain the observed cross-cultural variation in the MNL. This variation is clearest when comparing Westerners, who consistently show left-to-right SNARC effects (see Wood et al., 2008), to Arabic-speakers, who have shown reversed SNARC effects in four studies (Maier et al., 2015; Shaki et al., 2009, Shaki et al., 2012; Zebian, 2005). This cross-cultural difference has often been interpreted as (correlational) evidence for the Reading/Writing hypothesis, since people in these cultures read text in different directions. However, these differences can also be explained by cultural conventions for reading and writing *numbers*. For Westerners, numbers are written from left to right, so numbers tend to appear in increasing order from left to right on a variety of culture-specific artifacts, like graphs and charts, computer keyboards, and kindergarten walls. This explicit spatialization of numbers is also present in multi-digit 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.[11] These cultural conventions for reading and writing numbers cause Westerners and Arabic-speakers to see numbers arrayed differently in space. Therefore, the observed difference in the direction of the MNL across these cultures can be explained on the basis of the CORE principle – that is, on the basis of how numbers are spatialized.

Another cross-cultural difference in the MNL has been of special interest to researchers of numerical cognition: Hebrew-speaking Israelis 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

[11] 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, Goebel, & Shaki (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 that culture to cultures in which text and numbers are written in opposite directions. For simplicity, we use "Arabic-speakers" to refer to the people from these cultures.

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, several studies have found "flat" SNARC effects (i.e. null results) in Hebrew-speaking Israelis, despite the direction of written text in their culture (e.g. Fischer & Shaki, 2012; Shaki et al., 2009; cf. Fischer & Shaki, 2016; Zohar-Shai et al., 2017). To explain this pattern, researchers have proposed a hybrid account, according to which "reading habits for both words and numbers contribute to the spatial representation of numbers" (Shaki et al., 2009, p. 328). On this account, flat SNARC effects in Hebrew-speakers are the result of "their conflicting spatial associations for words and numbers" (ibid., p. 329). However, like the findings in Westerners and Arabic speakers, the findings in Hebrew speakers can be explained on the basis of the spatialization of numbers, alone.[12]

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. Therefore, whereas Westerners experience a consistent number mapping from left to right 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

[12] To be clear, the spatialization of both numerals and number words can vary independently from the direction of written text across cultures: The mapping of numerals can be congruent (e.g. Americans, Palestinians) or incongruent with the direct of text (e.g. Israelis); Likewise, the mapping of number words can be congruent (e.g. Americans, Palestinians) or incongruent (e.g. German) with the direction of text (see Moeller, Shaki, Göbel, Nuerk, 2014).

conflict between reading text and reading numbers -- nor is this explanation likely to be correct, given the complete 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.[13] The CORE principle predicts precisely the pattern of cross-cultural variation in the MNL that has been observed solely on the basis of cross-cultural variation in numerical notations: 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).

6.3 Experiential bases of the MTL

Beyond reading experience (Experiment 1; Casasanto & Bottini, 2014) and finger counting (Experiment 3), what other experiences can shape the MTL? According to the CORE principle, observing or performing any movement with consistent directionality should affect the MTL because it provides a correlation between progress through time and progress through space (e.g., rightward, leftward, upward, or downward; see Casasanto & Bottini, 2014). This space-time correlation is found in visual activities like reading English as well as non-visual 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; Nuñez & Sweetser, 2006), and by explicit spatial representations of time. For example, in Western cultures we place Monday to the left of Tuesday and January to the left of February on calendars, and the year 1999 to the

[13] 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).

left of 2000 on timelines and graphs. By systematically displaying earlier events on one side and later events on the other, these cultural artifacts provide the kind of experience that, according to the CORE principle, should be capable of shaping the MTL. Depictions of time tend to follow the direction of reading and writing across cultures and should therefore reinforce the same culture-specific space-time mappings as reading and writing, per se.

6.4 Experiential bases of the MNL

Beyond finger counting (Experiments 2 and 3), what other experiences can shape the MNL? According to the CORE principle, any experience with objects or events 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 numbers in increasing order either from left to right or from right to left.[14] Can experience with written numbers affect the MNL, as finger counting did here? CORE predicts that it should. Accordingly, 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

[14] Some cultural artifacts, like many 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 our Experiment 3, in which a single experience had independent effects on the MTL and MNL.

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 support to the claim that the MNL is shaped by experiences that spatialize numbers, whether across the fingers or across the page.

6.5 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 a consistent temporal order. When people count aloud, the word "one" is spoken before "two," etc. 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, changes in the MTL corresponded to changes in the 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 do so using 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 seconds, 12 hours, 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 in adults, it is overwhelmed by the influence of space-time correlations in experience.

6.6 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 lead some researchers to doubt their centrality in our mental representations of time and number, especially in the case of the MNL (e.g. Fischer et al., 2010; van Dijck & Fias, 2011; Fischer, 2006). For example, van Dijck & 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, Martin Fischer (2006) explains why *The Future of the SNARC Could Be Stark*, 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). Does the flexibility of the MNL (or any other spatial mapping) undermine its 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, 2017b), 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*. Whereas overhypotheses are conditioned by regularities in the natural world (and may therefore be universal), specific hypotheses are conditioned by particular aspects of people's linguistic, cultural, or bodily experience, and are therefore language-specific, culture-specific, or body-specific (Casasanto, 2017b).

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 position along a linear spatial path* (Casasanto & Bottini, 2014). The correlation between space and time is readily observable in moving objects: as objects travel farther more time passes. This correlation obtains regardless of an object's direction of travel and therefore gives rise to a metaphorical mapping between time and space that is direction-nonspecific. 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 position along a linear spatial path*, strengthening this 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 their 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 (which may not even be linear). On the basis of this experience, children could generate the overhypothesis, *Progress through numerical order corresponds to change in position along a (linear) spatial array*. This initial direction-agnostic association between space and number may serve as the basis for later direction-specific associations. 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 <u>rightward</u> change in position along a (linear) spatial array*. In left-to-right finger counting, progress through the numbers corresponds to rightward progress in space across the fingers. When children practice reading or writing numbers in order of the count list (but not when they read normal text), progress through the numbers corresponds to progress rightward across the blackboard or page. These experiences should increase the weight of evidence for an MNL in which small numbers are associated with the left and large numbers with the right.

According to HMMT, finger counting in one direction or another neither creates new space-number mappings nor eliminates old ones. Rather, our finger-counting training shifted the weight of evidence to one of the specific mappings entailed by the overhypothesized mapping, transiently strengthening or weakening participants' usual mappings. On this account, the flexibility of the MNL is not a symptom of deficiency, but is rather a product of the hierarchical structure of space-number metaphors. According to HMMT the MNL is culture-specific at one level of analysis, but universal at another.

6.7 Is there a universal left-to-right MNL in infants and non-human animals?

Findings in human infants and non-human 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). If people have such a directional mapping of numbers from birth, this discovery would conflict with a prediction of HMMT, according to which any universal early mapping of numerical order and spatial position should be direction-nonspecific. Do infants' space-number associations start out with or without direction? An examination of the findings that have been interpreted as evidence for a directional MNL in newborns and non-human animals reveals that these findings are subject to alternative explanations, and some results may not reflect space-number associations at all.

In one study, three-day-old chicks were exposed to dot arrays of varying number and then walked either to the left or right side of a central barrier (Rugani, Vallortigara, Priftis, & Regolin, 2015). Chicks tended to go to the left in response to smaller numerosities and to the right in response to larger numerosities. Although these findings are consistent with a left-to-right space-number mapping analogous to the MNL found in Westerners, they can also be explained by established patterns of hemispheric specialization for emotional motivation (Vallortigara, 2018; Brookshire & Casasanto, 2018; for further critique, see Nuñez & Fias, 2017). As one of the pioneers of this animal research cautioned, "the road from behavior to the underlying mechanisms in different species is a tortuous one" because any "resemblances in behavior [across species]…may be associated with completely different functions and underlying structures" (ibid., p. 6). Even if these findings reflect something about numerical cognition in these species, it is not clear what implications they would have for theories of numerical cognition in humans.

Do human infants show signs of a left-to-right MNL? To date, one study has addressed this question in newborns (de Hevia et al., 2017). Infants looked longer at the left side of a screen when they experienced a decrease in number (of auditory tones) and looked longer at the right side of the screen when they experienced an increase in number. The authors concluded that "the newborn human mind may be biased to relate representations of relative quantity to [left-right] spatial positions prior to any experience with a culturally mediated environment" (p. 5). However, they also acknowledge that they "cannot rule out the possibility that the effect depends on the simultaneous presence of numerical and non-numerical cues…as it is impossible to simultaneously control for all continuous variables for a single numerical stimulus (e.g., rate and duration) in this type of design" (ibid.)

Further research is needed to clarify how the initial evidence for left-to-right mappings of number in infants and non-human animals should be interpreted, and to determine the starting point for our culture-specific spatial representations of time and number.

7. Conclusion

How does culture shape our abstract concepts? These experiments show that different aspects of cultural experience have predictably different effects on conceptualizations of time and numbers. Whereas the mental timeline was shaped by aspects of experience that spatialize time, the mental number line was shaped by aspects of experience that spatialize numbers. The findings challenge the dominant accounts of cross-cultural variation in the MTL and MNL, according to which these mappings are shaped by reading/writing experience, directional scanning habits, or all spatially oriented activities. Rather than identifying an exhaustive set of experiences that shape each of these mappings across cultures, this research sought to test a general principle (i.e. the CORE principle) governing *which kinds of experience* can affect a given mapping – and which kinds of experience cannot. Although these experiments tested the effects of two kinds of experience (reading and finger counting) on two mental metaphors (the MTL and MNL), the results have implications beyond these experimental testbeds.

Just as reading is not the only experience that can shape the MTL (finger counting can too), finger counting is not the only experience that can shape the MNL (and may not even be the primary experience). Given the diversity and complexity of human cultures, there is likely no single experiential basis for either of these mappings, or perhaps for any mental metaphor. Rather, each mapping may be shaped by a family of experiences, limited only by the variety of ways in which the relevant source and target domain are correlated in people's experience. As the present results show, the set of experiences that can shape the MTL is different from the set of experiences that can shape the MNL (although they overlap). Each mental metaphor may be shaped by a unique set of experiences, and those experiences may vary across cultures; still, the ways in which a given experience affects a given mental metaphor may be governed by a universal set of cognitive principles. Therefore, this research clarifies not only the origins of the MTL and the MNL, but how the diversity of human experiences produces a diversity of human minds.

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