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Time and numbers on the fingers: Dissociating the mental timeline and mental number line

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Abstract

People use space to conceptualize abstract domains like time and number. This tendency may be a cognitive universal, but the specifics of people's implicit space-time and space-number associations vary across cultures. How does culture shape our abstract concepts? 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. The directions of both the MTL and MNL have long been assumed to depend on the direction in which people read and write text. Here we argue that this assumption is false, and show that the MTL and MNL are shaped by different aspects of cultural experience. In a training experiment, participants spatialized time and numbers in opposite directions across their fingers. Training changed the MTL and MNL in opposite directions, as predicted by a general principle called the CORrelations in Experience (CORE) principle: people spatialize abstract conceptual domains in their minds according to the ways these domains are spatialized in their experience.

Keywords: Conceptual metaphor; SNARC; Mental number line; Mental timeline; Space; Time; Embodied cognition

Introduction

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 kindergarten, 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, Fischer, & Göbel, 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 & Umlità, 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). Different cultures use space differently to conceptualize abstract domains like time and number. What aspects of cultural experience determine the direction of the MTL and the MNL?

Can reading text shape the MTL and/or MNL?

On the basis of cross-cultural variation, many scholars have concluded that the directions of both the MTL and MNL are determined by the direction in which people read and write text. Yet, upon examination, the evidence for this assumption is much stronger for the MTL than for the MNL.

The direction of the MTL correlates with the direction of reading and writing across cultures. 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 the corresponding reversal in the MTL (i.e. earlier on the right, later on the left; Arabic: Tversky et al., 1991; Hebrew: Fuhrman & Boroditsky, 2010; Ouellet, Santiago, Israeli & Gabay, 2010; cf., Tversky et al., 1991).

Testing whether reading experience can play a causal role in determining the direction of the MTL requires experimental intervention. In previous experiments (Casasanto & Bottini, 2014; Pitt & Casasanto, 2016), participants were randomly assigned to read text in either normal orthography (from left to right) or mirror-reversed orthography (from right to left) and classified 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 showed space-time congruity effects that were significantly reduced (Pitt & Casasanto, 2016) or completely reversed (Casasanto & Bottini, 2014), indexing a right-to-left MTL like that of Arabic speakers. Together, the correlational and experimental data support the claim that reading experience can determine the direction of the MTL.

Although it is widely assumed that reading experience also determines the direction of the MNL, there is little evidence to support this conclusion. 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. French: Dehaene et al., 1993; Scots: Fischer, 2008; Canadians: Shaki et al., 2009). However, there is little evidence that people who read from right to left (e.g. in Arabic, Hebrew) have reversed MNLs. In their seminal study establishing the Spatial-Numerical Association of Response Codes (SNARC) effect, Dehaene et al. (1993) found "no evidence" of a reversed SNARC effect in Iranians who had extensive exposure to right-to-left orthography.[1] One study found a reversed SNARC effect in Arabic-speaking Palestinians (Shaki et al., 2009) but numerous studies have found either null or standard SNARC effects in Hebrew-speaking Israelis, despite the way they read and write text (Shaki et al., 2009; Fischer & Shaki, 2016; Zohar-Shai, Tzelgov, Karni, & Rubinsten, 2017). Another study has demonstrated a reversed SNARC effect among Arabic-speakers (Zebian, 2005), but this finding is uninterpretable because Arabic-English bilinguals in that study showed reversed SNARC effects that were numerically *stronger* than those of Arabic monolinguals (and English monolinguals showed no significant SNARC effect). Although these studies are often cited as (correlational) evidence that reading shapes the MNL, they provide no clear support for this claim (see also Fischer, Shaki, & Cruise, 2009).

To date, there have been two direct experimental tests of the effect of reading experience on the direction of the MNL, neither of which showed any effect of reading.[2] First, in the original SNARC paper, French participants responded to number words presented in either standard or mirror-reversed orthography (Dehaene et al., 1993: Experiment 8). Orthography had no effect on the strength or direction of the SNARC; Participants showed normal SNARC effects regardless of the direction in which they read. Second, in a study by Pitt & Casasanto (2016), participants read English text either normally or mirror-reversed during a training phase (for about 24 minutes) and then performed a standard test of the SNARC effect. Again, participants showed standard SNARC effects that did not differ between conditions; reading direction had no effect on the MNL. (This null effect of reading training cannot easily be attributed to a lack of exposure to reversed orthography because the same training had a reliable effect on the MTL, in the same participants. Reading changed the MTL but did not change the MNL.) If reading and writing do not determine the direction of the MNL, then what kind of experience does?

Can finger counting shape the MNL?

The direction of the MNL has also been attributed to finger counting. In a study that provides correlational support for this proposal, people whose finger-counting routines start with the left hand (habitual left-starters) were found to be more likely to show a standard SNARC effect than those who started with their right hand (habitual right-starters; 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).

One study has tested whether finger counting can play a causal role in determining the direction of the MNL (Pitt & Casasanto, 2014). Participants were randomly assigned to count on their fingers either from left to right or from right to left across their hands for about 15 minutes. Participants who counted left-to-right showed reliable standard SNARC effects, indexing the right-to-left MNL typical of Americans. Participants who counted on their fingers from right to left showed SNARC effects that were significantly reduced. Taken together, these findings suggest that, unlike reading experience, finger-counting experience can determine the direction of the MNL.

Correlations in Experience: The CORE principle

Why would reading experience determine the direction of the MTL but not the MNL? Why would the MNL be shaped by finger counting but not by reading? The answers can be found in the acts of reading and finger counting, which differ in what they spatialize. When reading English text, people's eyes start on the left side of the page at an earlier time and end on the right side at a later time. In this experience, progress through time correlates with progress (rightward) through space. By contrast, there is no analogous correlation between space and number in the act of reading ordinary text (as opposed to reading numbers, per se). Moving rightward across the page corresponds to moving *later in time*, but it does not correspond to moving *greater in number* (unless people count words as they read, which is unlikely). Therefore, reading text provides a correlation between space and time but not between space and number. By contrast, the act of finger counting *does* provide a correlation between space and number; during finger counting, people typically spatialize smaller numbers on one hand and larger numbers on the other hand. When numbers increase in the same direction on both hands, progress through space corresponds to progress through the count list (Pitt & Casasanto, 2014). What role do these space-time and space-number correlations play in the ways people conceptualize time and number?

We propose that the way an abstract domain (like time or number) is spatialized in people's minds depends on how that domain is spatialized in their experience. On this account, which we call the CORrelations in Experience (CORE) principle, the MTL should be shaped by experiences that spatialize time (i.e. provide a space-time correlation) whereas

[1] The average SNARC slope was 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).

[2] In a study by Shaki & Fischer (2008), Hebrew-Russian bilinguals showed weaker SNARC effects after reading in Hebrew than after reading in Russian. However, in these experiments, reading direction was confounded with language. Therefore, any difference between conditions may be due to other cultural factors that differ across these language groups.

the MNL should be shaped by experiences that spatialize numbers (i.e. provide a space-number correlation). Reading text spatializes time but not numbers, therefore reading should shape the MTL but not the MNL. Finger counting spatializes numbers, therefore it should shape the MNL. These predictions of the CORE principle are borne out by the pattern of empirical findings discussed above.

Yet, the CORE principle makes an additional, untested prediction with regard to which mental mappings should and should not be shaped by finger counting. When counting fingers, people not only progress from one number to the next, they also progress from one moment to the next through time. The act of finger counting (like the act of reading) starts on one side of space at an earlier time and ends on the other side at a later time. Whereas reading spatializes time but not numbers, finger counting spatializes *both time and numbers*. Therefore, according to the CORE principle, finger counting should be able to reshape both the MTL and the MNL.

Here we tested whether finger counting can shape both the MTL and MNL. To do so, we designed a novel finger-counting training experience. Normally, when people count on their fingers, they count up (e.g. 1, 2, 3…). In this counting routine, progress through time is perfectly confounded with progress through the count list; as time progresses, numbers get larger. However, when counting *down* on the fingers (e.g. 9, 8, 7…), time and number progress in *opposite* directions; As time progresses, numbers get *smaller*. By unconfounding time and numbers in this way, here we can assess independent effects of training on the MTL and MNL. If people spatialize abstract domains in their minds according to the way those domains are spatialized in their experience, then this finger-counting training, which spatializes time and numbers in opposite directions, should have opposite effects on the MTL and MNL.

Method

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).

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 auditorally. Participants were not exposed to any written text during either training or testing.

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 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.

After participants were familiarized with the leftward or rightward finger-counting pattern, they practiced the pattern during a computer-based training task. In each training trial, participants heard a number between one and ten. 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 32 times (with a short break in the middle). At the end of training, participants were instructed to do the same counting task but "as quickly and accurately as possible." 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.

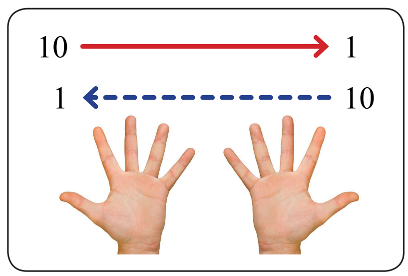

Figure 1. Training procedure. Participants either counted down to the right (solid arrow) or down to the left (dashed arrow).

Test Phase. In the (true) test phase, which immediately followed the training phase, participants completed one of two tasks: a *Number task* to measure space-number congruity effects (modeled on classic tests of the SNARC effect; see Fischer & Shaki, 2014, for review) or an analogous *Time task* to measure space-time congruity effects. 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 Time 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. For one block, they used the left-hand key for small numbers / earlier months and the right-hand key for large numbers / later months. In the other block, this response-mapping was reversed and block order was counterbalanced across participants. At the beginning of each block, the experimenter asked the participant to raise the hand corresponding to each of the responses to ensure that the response mapping was understood. In each block, the eight unique stimuli (number words or month names) were played in random order 12 times, composing 192 test trials per participant. Participants were instructed to focus their gaze on the white dot that appeared in the center of the computer screen during the test trials and to respond "as quickly and accurately as possible." Each trial began with a

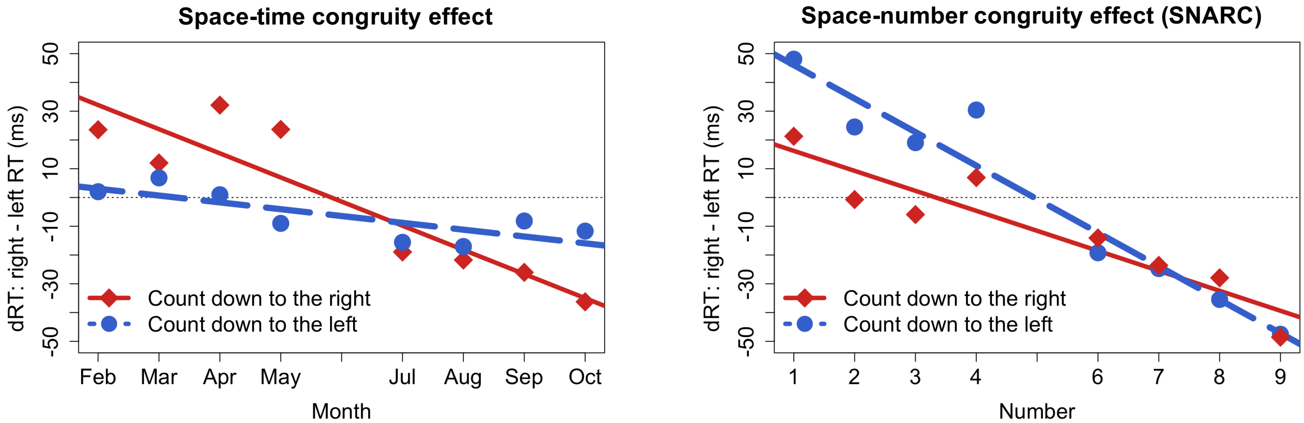

Figure 2. Finger-counting training changed space-time (left) and space-number (right) congruity effects in opposite directions.

variable delay period (500-1000 ms) and ended automatically with an auditory alert if no response was given within 1.5 seconds after stimulus onset. In each finger-counting condition, half of the participants were randomly assigned to the Number task and the other half to the Time task.

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

Results

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

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 and compare 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 in R (Baayen, Davidson, & Bates, 2008; Bates, Maechler, Bolker, & Walker, 2015; R Development 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.[3] In order to approximate a normal distribution of residuals, the data for each model was first transformed according to the results of a Box Cox test (Osborne, 2010).

Space-Time Associations. RTs greater than 2.5 standard deviations from subject means were removed (2.18% of accurate responses), following Shaki & Fischer (2008). In the counting-down-to-the-right condition (10→1), in which participants started on the left and ended on the right, the space-time congruity effect was significant ($\chi^2(1)$=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 2, 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). 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.

Comparison of space-number and space-time effects. To compare the effect of training condition on space-number and

[3] For comparison with other findings, we also report and plot congruity effects 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.

space-time congruity effects, we conducted an lmer model on log-transformed RTs with response hand, ordinal position of months or numbers, training condition, and task as predictors, with random slopes and intercepts for subjects. 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.

General Discussion

The directions of the mental timeline and mental number line both vary across cultures, and both are often attributed to culture-specific habits of reading and writing. Here we tested an alternative proposal, according to which the MTL and MNL are shaped by different aspects of cultural experience. During a training task, participants spatialized time and numbers in opposite directions across their fingers. This training experience had independent and opposite effects on the MTL and MNL; the MTL changed according to the way time was spatialized during training (despite the way numbers were spatialized) and the MNL changed according to the way numbers were spatialized during training (despite the way time was spatialized). These results support the proposal that cross-domain mappings in the mind are selectively shaped by the aspects of experience in which the domains are correlated; The MTL is shaped by aspects of experience that spatialize time whereas the MNL is shaped by aspects of experience that spatialize numbers.

These results also militate against a skeptical account of the one previous experiment that tested the effects of finger counting on the MNL. In that experiment (Pitt & Casasanto, 2014), the finger-counting training always spatialized time and numbers in the same direction; Participants counted up (e.g. 1, 2, 3…) on their fingers either to the right or to the left. Therefore, in principle the effects on the MNL could have resulted from the spatialization of numbers or the spatialization of time (or both) during training. By contrast, here the MNL changed according to the way numbers were spatialized, even though time was spatialized the other way.

How experience shapes mental metaphors

Both the MTL and MNL can be considered *mental metaphors*: point-to-point mappings between analog continuums in two different conceptual domains, in which the *source domain* (e.g. space) serves as a scaffold for representations in the *target domain* (e.g. time, number), which is typically more abstract (Casasanto, 2010; Lakoff & Johnson, 1980). By hypothesis, the specifics of these mental metaphors are established through correlations in particular kinds of experience (Casasanto, 2013). Specifically, we propose that source and target domains are mapped in the mind according to the way they are correlated in experience; the CORE principle. The results we found here provide strong support for this principle, showing that two cross-domain correlations (i.e. space-time and space-number correlations) within a single experience can *selectively* change the metaphorical mapping between those domains.

Importantly, we do not wish to suggest that finger-counting experience is the sole (or even the primary) determinant of cross-cultural variation in the direction of either the MTL or the MNL. Rather, we propose that each mapping is shaped by a family of experiences, of which finger-counting experience may be one; The MTL is shaped by experiences that spatialize time and the MNL is shaped by experiences that spatialize numbers. Although these families of experiences can overlap (as in the case of finger counting), they may be largely distinct, because different experiences spatialize different domains. Starting from the CORE principle, we can determine which experiences *should* and *should not* shape the mapping between a given source and target domain by asking what experiences do and do not provide a correlation between the domains.

Whereas the act of reading provides a correlation between space and time, reading does not provide a correlation between space and number. Accordingly, reading experience has been shown to change the MTL, and not to change the MNL (Casasanto & Bottini, 2014; Pitt & Casasanto, 2016), challenging the widely held belief that "The particular direction of the spatial-numerical association seems to be determined by the direction of writing" (Deheane et al., 1993).

By contrast, there *is* a correlation between space and numbers in the act of finger counting. Unlike reading, finger counting can reshape the MNL, as shown here as well as in a previous experiment in which participants counted "up" on their fingers (i.e. 1, 2, 3…) during training. Whether time and numbers progressed in the same direction (Pitt & Casasanto, 2014) or in opposite directions (as in the present experiment), the spatialization of numbers on the fingers reliably changed the MNL, as predicted by the CORE principle.

Where else (besides the fingers) are numbers spatialized? Although numbers are not systematically spatialized in ordinary text, they are systematically spatialized on written number lines, which appear on calendars, graphs, rulers, computer keyboards, and other artifacts. Accordingly, space-number associations can be modulated by changing the left-right positions of smaller and larger numbers on the page (independent of the direction of written words; Fischer et al., 2010).

Conclusion

The mental timeline and mental number line have different experiential bases; whereas the the MTL is shaped by aspects of experience that spatialize time, the MNL is shaped by aspects of experience that spatialize numbers. The present findings challenge the widespead assumption that the direction of the MNL is determined by reading and writing experience. Rather, the MNL may be shaped by a variety of experiences that, unlike reading, array numbers in space. These results also establish finger-counting as a second experience (in addition to reading) that can shape the MTL. More broadly, these findings provide strong support for the CORE principle of mental mentaphors; mappings in the mind reflect correlations in experience.

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