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Reading experience shapes the mental timeline but not the mental number line

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Abstract

People conceptualize both time and numbers as unfolding along a horizontal line, either from left to right or from right to left. The direction of both the mental timeline (MTL) and the mental number line (MNL) are widely assumed to depend on the direction of reading and writing within a culture. Although experimental evidence supports this assumption regarding the MTL, there is no clear evidence that reading direction determines the direction of the MNL. Here we tested effects of reading experience on the direction of both the MTL and MNL. Participants read English text either normally (from left to right) or mirror-reversed (from right to left). After normal reading, participants showed the space-time associations and space-number associations typical of Westerners. After mirror reading, participants' space-time associations were significantly reduced but their space-number associations were unchanged. These results suggest that the MTL and MNL have different experiential bases. Whereas the MTL can be shaped by reading experience, the MNL is shaped by other culture-specific practices through which people experience numbers arrayed in left-right space.

Keywords: SNARC; Mental number line; Mental timeline; Space; Time; Reading direction; Numerical cognition

Introduction

Across many cultures, people use left-right space to think about both time and number. 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 have been demonstrated in hundreds of experiments, most often 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). These spatial mappings of time and number are also evident in people's spontaneous gestures (Casasanto & Jasmin, 2012) and eye movements (Fischer, Castel, Dodd & Pratt, 2003; Loestscher, Bockisch & Brugger, 2008) across lateral space.

What determines the directions of the MTL and 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, upon examination, the evidence for this assumption is much stronger for the MTL than the MNL.

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 events on the right, later events on the left; Arabic: Tversky, Kugelmass & Winter, 1991; Hebrew: Fuhrman & Boroditsky, 2010; Ouellet, Santiago, Israeli & Gabay, 2010; cf., Tversky et al., 1991). Despite this clear correlation, it is not known to what extent 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 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 requires experimental intervention. Casasanto and Bottini (2014) randomly assigned Dutch speakers to read text in either normal orthography (from left to right) or mirror-reversed orthography (from right to left) while classifying events as either earlier or later in time. Participants who read normally were faster to classify earlier events with their left hand and later events with their right hand, reflecting the left-to-right MTL typical of Westerners. By contrast, those who read mirror-reversed text showed the opposite pattern of RTs, showing a right-to-left MTL like that of Arabic speakers. Together, the correlational and experimental data provide strong support for the claim that reading experience can determine the direction of the MTL.

In the case of the MNL, however, the evidence is much less clear. In general, the direction of the MNL covaries with the direction of written text in a culture: Westerners tend to show MNLs that increase from left to right (e.g. French: Dehaene et al., 1993; Scots: Fischer, 2008; Canadians: Shaki, Fischer, & Petrusic, 2009), whereas people from some Arabic cultures show MNLs in the opposite direction (i.e. smaller numbers on the right, larger numbers on the left), consistent with the right-to-left reading direction in their cultures (Palestinians: Shaki et al., 2009; Lebanese: Zebian, 2005). This cross-cultural variation has lead to a general consensus that, like the MTL, the MNL's direction is determined by the direction of orthography.

Yet, overall, the claim that reading or writing experience determines the direction of the MNL is neither well-supported by empirical evidence nor clearly motivated. First, the direction of people's MNLs appears to be only loosely correlated with the direction in which they read and write text. In their seminal study establishing the Spatial-Numerical Association of Response Codes (SNARC) effect, Dehaene et al. (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 who had extensive exposure to right-to-left orthography. Another study found a reversed SNARC effect in Arabic-speaking Palestinians but no SNARC effect in Hebrew-speaking Israelis, who also read text from right to left (Shaki et al., 2009). One other study has demonstrated a reversed SNARC effect among Arabic-speakers (Zebian, 2005), but contrary to predictions, Arabic-English bilinguals showed reversed SNARC effects that were numerically *stronger* than those of Arabic monolinguals (and English monolinguals showed no significant SNARC effect). Although these three studies are often cited as evidence for the proposal that reading direction shapes the MNL, none of them clearly support this proposal (see also Fischer, Shaki, & Cruise, 2009).

The only direct experimental test of the effect of reading experience on the direction of the MNL produced a null result[1]. French participants responded to number words presented in either standard or mirror-reversed orthography. Participants showed normal SNARC effects in both conditions; Orthography had no effect on the strength or direction of the SNARC (Dehaene et al., 1993: Experiment 8). In spite of this result, the researchers concluded that "[t]he particular direction of the spatial-numerical association seems to be determined by the direction of writing," (Dehaene et al., 1993, pg. 394) – a conclusion that has been widely accepted for more than two decades. Yet, there is little evidence to support this conclusion, and some clear reasons to doubt it, on the basis of both correlational and experimental data.

Why might reading experience determine the direction of the MTL but not the MNL? The answer may be found in the experience of reading. 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. This experiental correlation between space and time in orthography is sufficient to determine the direction of the MTL (Casasanto & Bottini, 2014).

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). Reading or writing text creates an experiential link between space and time, but not between space and number. As such, the proposal that reading experience plays a functional role in determining the direction of the MTL is well motivated, but the proposal that reading experience plays a functional role in determining the direction of the MNL is not.

Here we 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. After reading training, we assessed the strength and direction of participants' MTLs and MNLs 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. Alternatively, if the directions of the MTL and MNL are determined by different kinds of experience, then mirror-reversed reading should reduce (or reverse) the space-time congruity effect but not the space-number congruity effect.

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 reading condition (n=32) and the other half to the reversed 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. They were seated in front of a 24-inch Apple iMac computer (with the keyboard and mouse removed) and were told that they would be asked some comprehension questions after reading. Text appeared in black on a white background and spanned the width of the screen. The text, which was excerpted from *Zen and the Art of Motorcycle Maintenance* (Persig, 1974), consisted of 2,964 words and

[1] 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.

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.

Test Phase. The test phase immediately followed the training phase and consisted of three tasks in which participants were instructed to respond "as quickly and accurately as possible." In the months 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. 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 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. In the digits task, numbers were presented as Arabic numerals; in the number words task, they were presented as English number words. In training and test, all instructions and stimuli appeared in capital letters and were presented in normal orthography in the standard reading condition and in mirror-reversed orthography in the reversed reading condition.

In each block, 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 clarity of the response mapping. Each trial began with 500 ms of a black screen followed by a fixation cross whose duration varied uniformly between 500 and 1000 ms. Throughout testing, all numbers and words were presented in white on a black background at the center of the screen. The order of months and number tasks was counterbalanced across participants such that the months 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 digits and number words tasks was counterbalanced across participants.

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

Results

Three subjects who failed to follow instructions and one who guessed the purpose of the training were replaced. The error rate was significantly higher in the reversed reading condition (4.16%) than in the standard reading condition (3.20%; $\chi 2(1, N=64)=16.03$, $p=.0006$) and significantly higher in the months task (4.11%) than in the number words task (3.28%; $\chi 2(1, N=64)=7.94$, $p=.005$; all other p's > .10). Although statistically significant, these differences in error rates were very small (less than 1%). We excluded inaccurate trials (3.68%) and accurate trials with RTs less than 200ms or greater than 2500ms (2.53%).

To evaluate space-time congruity effects, months were coded for ordinal position in the calendar year. We conducted an analysis of variance (ANOVA) on RTs with response hand and ordinal position of months as predictors. We used the same analysis to evaluate space-number congruity effects: RTs were entered into an ANOVA with response hand and ordinal position of numbers as predictors (a measure of the SNARC effect; see Dehaene et al., 1993; Gevers et al., 2010; van Dijck & Fias, 2011)[2]. In all tests, RTs were reciprocal-transformed to approximate a normal distribution of residuals and subjects were included as a random effect.

Space-Time Associations

RTs greater than 2.5 standard deviations from subject means were removed (4.47%). In the standard reading condition, the interaction between response hand and position was highly significant ($F(1, 3622)=46.15$, $p<.0001$), indicating a reliable standard space-time congruity effect in which earlier months were associated with the left and later months were associated with the right (mean slope=-18.61ms/position). A significant space-time congruity effect was also found in the reversed reading condition ($F(1, 3570)=6.98$, $p=.008$; mean slope=-8.34ms/position); of primary interest, this effect was significantly weaker than in the standard reading condition ($F(1, 7192)=8.09$, $p=.004$; Fig. 1, left). Reading direction reliably changed the MTL, in the predicted direction.

Space-Number Associations

Digits Task RTs greater than 2.5 standard deviations from subject means were removed (4.95%). In the standard reading condition, the interaction between response hand and position was highly significant ($F(1, 3681)=44.01$, $p<.0001$), indicating a reliable standard SNARC effect in which small numbers were associated with the left and large numbers were associated with the right (mean slope=-7.68ms/digit). A nearly identical SNARC effect was found

[2]For comparison with other findings, we report and plot the SNARC effect in each task as a regression slope, following Fias, Brysbaert, Geypens, & Géry (1996), regressing dRT values (dRT=right-hand – left-hand RT) for each number or month over ordinal position. Although these slopes can also be used for inferential statistics, using them here would be inappropriate for several reasons. For example, statistical tests across these data points cannot include random effects of subjects, which can increase Type I error rate. Furthermore, because Fias et al.'s method collapses over large amounts of data (here, a 128:1 compression) it is unfit for testing the higher-order (3-way and 4-way) interactions on which our experimental questions depend.

in the reversed reading condition (F(1, 3604)=42.73, p<.0001; mean slope=-7.94ms/digit). The difference in the SNARC effects across conditions did not approach significance (F(1, 7285)=.05, p=.82).

Number Words Task RTs greater than 2.5 standard deviations from subject means were removed (5.02%). In the standard reading condition, the interaction between response hand and position was significant (F(1, 3650)=11.20, p=.0008), indicating a reliable standard SNARC effect (mean slope=-5.77ms/digit). A significant standard SNARC effect was also found in the reversed reading condition (F(1, 3625)=9.69, p=.002; mean slope=-2.75ms/digit). The difference in the SNARC effects across conditions did not approach significance (F(1, 7275)=.01, p=.92).

Comparison of number tasks To compare the effect of reading condition between the digit task and the number words task, we conducted an ANOVA on reciprocal-transformed RTs with position, response hand, reading condition, and task as predictors. The effect of reading condition on the SNARC effect did not differ between the two number tasks (F(1, 14622)=.02, p=.89). We therefore combined the RT data from the digits task and the number words task, doubling our item-wise power to detect an effect of reading direction on the MNL.

Number Tasks Combined In the standard reading condition, the interaction between response hand and position was significant (F(1, 7366)=47.69, p<.0001), indicating a reliable standard SNARC effect (mean slope=-6.69ms/digit). A reliable standard SNARC effect was also found in the reversed reading condition (F(1, 7264)=35.16, p<.0001; mean slope=-5.10ms/digit). Of primary interest, the SNARC effects did not differ across reading conditions (F(1, 14630)=.12, p=.73; Fig. 1, right). Reading direction had no effect on the direction of the MNL.

Comparison of time and number tasks To compare the effect of reading direction on the space-time and space-number congruity effects, we used a linear mixed-effects model in R. Reciprocal-transformed RTs were predicted by response hand, ordinal position, reading condition, and task, with random slopes and intercepts for subjects. The effect of reading condition on the space-time congruity effect was reliably stronger than the effect of reading condition on the space-number congruity effect ($\chi^2(1)=7.99$, p=.005). The significant effect of reading experience on the MTL was greater than its non-significant effect on the MNL.

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 the effect of reading direction on the direction of 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 provide evidence that reading direction can influence the direction of the MTL, but challenge the claim that reading direction shapes the MNL.

These findings address two shortcomings of the only other experimental test of the effect of reading direction on the MNL. Dehaene and colleagues (1993; Experiment 8) found no effect of reading direction on the SNARC effect. In principle, this null effect could result 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-reveresd text that participants received was sufficient to influence spatial mappings in their minds. In the current study, (a) we included a training phase to greatly increase participants' exposure to mirror-reversed text, and (b) we included a manipulation check: although reading training had no effect on the participants' MNL it had a highly significant effect on their MTL. As

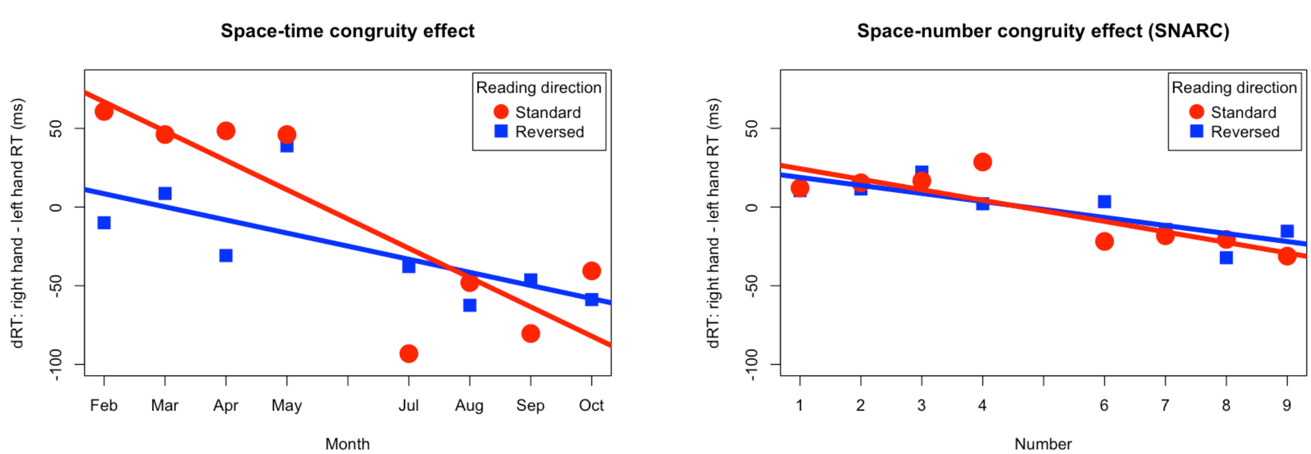

Figure 1. Left: Significant space-time congruity effects differed across reading conditions. Right: Significant space-number congruity effects did not differ across conditions (standard SNARC effect).

such, the lack of such 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, we had twice as much item-wise power to detect differences in space-number congruity effects as space-time congruity effects.

How experience shapes mental metaphors

Why does reading experience shape the MTL but not the MNL? Both space-time associations and space-number associations 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). The specifics of these mental metaphors are established through correlations in particular kinds of experience (Casasanto, 2013). Manipulating the kind of experience in which source and target domains are correlated should affect the mapping between them; manipulating other kinds of experience should not. This principle predicts the pattern of results we find here: space and time are correlated in the experience of reading text, but space and number are not. Therefore, manipulating reading experience affected the MTL but not the MNL.

Experiential bases of left-right time mappings What kinds of experience provide a correlation between space and time? In the act of reading, as people move their attention through space in either one direction or the other they also "move" through time. When reading each line of an English text, the reader's eyes begin on the left side (at an earlier time) and end on the right side (at a later time). This correlation between progress through time and progress *rightward* through space results in an MTL in which earlier events are associated with the left and later events are associated with the right. In other cultures, reading from right to left produces an MTL that progresses in the opposite direction. Although experience with orthography may be sufficient to determine the direction of the MTL in the laboratory (Casasanto & Bottini, 2014), it is likely that beyond the lab reading experience combines with other culture-specific experiences to shape the MTL: experiences like using calendars, graphs, or written timelines, which also provide a correlation between space and time.

Experiential bases of left-right number mappings What kinds of experience provide a correlation between space and number? There appears to be more than one answer. Here we consider 3 possible experiential bases of space-number mappings: reading and writing text; reading and writing numbers; and finger counting. All three of these practices vary across groups of people, and all three correlate roughly with the direction of the MNL across cultures. Only the last two practices, however, appear to be *causally related* to the direction of the MNL.

Reading and writing text Whereas the act of reading provides a correlation between space and time (no matter what the content of the text may be), reading does not provide a correlation between space and number. Without providing such a correlation, how could reading experience influence the MNL?

In principle, the direction of written text could have an *indirect* influence on the direction of the MNL, via the MTL. Starting in childhood, people experience numbers in a consistent temporal order in both speech and writing. 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 with the left and numbers that occur later with the right, producing a culture-specific MNL that reflects reading direction.

However, the present findings do not support this account. To the degree that the direction of the MNL depends on the direction of the MTL, changes in the MTL should cause corresponding changes in the MNL. Contrary to these predictions, changes to the MTL did not produce changes to the MNL in our participants, who showed standard space-number congruity effects regardless of differences in their space-time congruity effects. These findings, therefore, provide no evidence for either a direct or an indirect effect of reading direction on the MNL.

Reading and writing numbers Although numbers are not systematically spatialized in text, they are systematically spatialized on written number lines, which appear on calendars, graphs, rulers, computer keyboards, and other cultural artifacts. Changing the relative left-right positions of smaller and larger numbers has been shown to modulate the SNARC effect. In a training experiment, reading recipes in which large numbers appeared on the left of the page and small numbers appeared on the right caused a positive shift in the slope of participants' SNARC effects (compared to the opposite spatialization of numbers), *even though reading direction was held constant across conditions* (Fischer, Mills, & Shaki, 2010). Thus, the spatialization of written numbers on a page can influence the MNL even when it is in direct conflict with the direction of written words.

Finger counting Like written number lines, finger counting provides a correlation between space and number. In the act of finger counting, each number is assigned to a distinct location in lateral space. Individual differences in finger-counting habits correspond to differences in the SNARC effect: People who start counting on their left hand (left-starters) were found to be more likely to show a standard SNARC effect than right-starters (Fischer, 2008). Likewise, when responding to single digits using all 10 fingers, people are fastest to respond to single digits when the response mapping between numbers and fingers matches their own finger-counting routine (DiLuca et al., 2006). In an experimental test of the role of finger counting experience in determining the direction of the MNL, participants were trained to count on their fingers either from left to right or from right to left. Participants who counted left-to-right showed a standard SNARC effect whereas those who counted right-to-left showed no SNARC effect. Less than 15 minutes of finger counting from right to left caused a reliable change in the MNL (Pitt & Casasanto, 2014). By contrast, in the present study, more than twice as much experience reading text from right to left caused no such change in the MNL.

Conclusions

Here we challenge the assumption that the directions of both the MTL and the MNL are determined by the direction of reading and writing. Less than 40 minutes of reading mirror-reversed English text reliably changed participants' space-time associations, but left their space-number associations unchanged. These results suggest that the directions of the MTL and MNL are determined by different kinds of experience. Whereas the MTL is shaped by experiences that, like reading, provide a correlation between space and time, the MNL is shaped by other culture-specific experiences that, like finger counting, provide a correlation between space and number.

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