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ORIGINAL ARTICLE

Reading direction and spatial effects in parity and arithmetic tasks

Maham Azhar[1] · Yalin Chen[1] · Jamie I. D. Campbell[1]

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Abstract

This study investigated the relationship between numerical and spatial processing and reading direction, conducting conceptual replications of the Shaki et al. (Psychonomic Bulletin & Review 16(2): 328–331, 2009) parity task and the Mathieu et al. (Cognition 146: 229–239, 2016, Experiment 1) simple addition (e.g., $3+2$) and subtraction (e.g., $3-2$) task. Twenty-four left-to-right readers (LTR) and 24 right-to-left readers (RTL) were tested. The response time (RT) analysis of the parity task presented a robust spatial-numerical association of response codes (SNARC) effect (left-side response advantage for smaller numbers and right-side advantage for larger numbers) for LTR but not RTL readers. In the arithmetic task, the three problem elements (e.g., $3+4$) were presented sequentially with the second operand displaced slightly to the left or right of fixation. RTL but not LTR readers presented a RT advantage for subtraction relative to addition with a right-shifted second operand compared to it being left-shifted. This is consistent with a spatial bias linked to native reading direction. For both reading-direction groups, effects of the left vs. right side manipulation in the arithmetic or parity task did not correspond to parallel effects in the other task. The results imply that the parity-based SNARC effects and side-related effects in cognitive arithmetic are not equivalent measures of space-related processes in cognitive number processing and likely reflect distinct mechanisms.

Introduction

Theoretical links among cognitive representations of number, space and time have been supported by behavioral, neuropsychological, and brain imagining studies of humans and non-human primates (Fias & Bonato, 2018; Fischer & Shaki, 2018; Shaki, Pinhas, & Fischer, 2018; Walsh, 2003; Knops, 2018). Dehaene, Bossini and Giraux (1993) were the first researchers to observe a human behavioral relationship between numerical and spatial cognition. They demonstrated a spatial–numerical association of response codes (SNARC) effect using a parity-judgment task in which participants indicated whether a presented number (i.e., 1, 2, 3, 4, 6, 7, 8, 9) was odd or even by pressing a left-side or right-side response key. They found that right-side responses were faster than left-side responses for large numbers (i.e., 6, 7, 8, 9), whereas left-side responses were faster than right-side responses for small numbers (i..e., 1, 2, 3, 4). They proposed that the parity task activates a visuo-spatial mental number line (MNL) that is spatially organized from left (small numbers) to right (large numbers). RT is faster when numerical magnitude on the MNL and response side are congruent relative to incongruent trials.

Since then, substantial evidence has emerged to support a left-to-right MNL (Fischer & Shaki, 2018). For example, speed to detect a target in the left or right visual field was faster following a small or larger number, respectively (Casarotti, Michielin, Zorzi, & Umiltà, 2007; Fischer, Castel, Dodd & Pratt, 2003). Nonetheless, recent findings have challenged the MNL theory leading to the proposal that spatial or direction-related bias effects arise in working memory and reflect the serial-order processing of verbal numbers in working memory (e.g., Abrahamse, van Dijck & Fias, 2016; Fias & Van Dijck, 2016). In this view, spatial codes derive from a temporary and task-specific mapping of number items to a spatial template in working memory. In contrast, the MNL account proposes that spatial codes are an inherent component of long-term number representations that are recruited regardless of task context.

✉ Jamie I. D. Campbell
jamie.campbell@usask.ca

[1] Department of Psychology, University of Saskatchewan, 9 Campus Drive, Saskatoon, SK S7N 5A5, Canada

Reading direction and the SNARC Effect

A central element in the present research is that the direction of the SNARC may be culturally determined. Previous research suggests that the direction of the mapping of space to numbers depends on language and perhaps more specifically on the direction of reading. Dehaene, et al. (1993) found that Iranian right-to-left readers' SNARC effect in the parity task tended to be reversed relative to left-to-right readers, with small numbers responded to faster with a right-side response and larger numbers responded to faster with a left-side response. Among these participants, those who lived longer in a left-to-right reading environment (France in this case) and acquired a second language earlier demonstrated a "Western" left-to-right SNARC effect. In contrast, those who recently moved to France from Iran and acquired a second language late, presented a weak or reversed (right-to-left) SNARC effect. This cultural influence on the SNARC effect was reinforced by Shaki, Fischer and Petrusic (2009) (see also Viarouge Hubbard & Dehaene, 2014; Zebian, 2005; Zohar-Shai, Tzelgov, Karrni & Rubinsten, 2017) who tested three groups of participants—Palestinian, Israeli and Canadian. Stimuli were Arabic numbers for Israeli and Canadian participants and Indic (East Arabic) numbers for the Palestinian participants. Shaki et al. found that the SNARC effect depended on the agreement between reading direction for both written words and numbers (but see Ito & Hatta, 2004). Specifically, Canadian participants who were left-to-right readers (for words and Arabic numbers) demonstrated a left-to-right SNARC effect; while Palestinian participants who were native right-to-left readers (for words and Indic numbers) demonstrated a reverse SNARC effect suggesting to a reverse mapping of numbers to space. When the reading direction of numbers and words did not agree, which was the case for Israeli participants, no such spatial biases were observed.

Reading direction and arithmetic

Spatial or directional biases have also been observed with addition and subtraction problems. The earliest observation of spatial biases in arithmetic was interpreted as an operational momentum effect—a trend to overestimate addition problems and underestimate subtraction problems (McCrink, Dehaene & Dehaene-Lambertz, 2007). While some researchers posit semantic associations between numbers and operation signs to explain spatial biases in arithmetic (e.g., Hartmann, Mast, & Fischer, 2015, 2017, 2018; Pinhas & Fischer, 2008; Pinhas, Shaki & Fischer, 2015), others attribute these biases to an attentional shift on a MNL (Li et al., 2018; Masson & Pesenti, 2014; Mathieu et al., 2016; McCrink et al., 2007).

Mathieu, et al. (2016) were among the first researchers to demonstrate the effect of a visuospatial attention shift on arithmetic performance per se (see also Wiemers, Lindemann & Bekkering, 2014). In their experimental paradigm, the components of single-digit addition and subtraction problems were presented sequentially: the first operand (O1), the operator (e.g., + or −), then the second operand (O2). The position of O2 was displaced to the right or left of central fixation and the inter-stimulus interval (ISI) between operator offset and O2 onset was manipulated (150, 300, or 450 ms). Mathieu, et al. (2016) referred to these intervals as stimulus onset asynchronies (SOAs), but their Fig. 1 correctly depicted ISIs of 150, 300 or 450 ms following *offset* of the 150 ms operator.[1] With the 300 ms ISI, mean RT was 34 ms faster for addition when the second operand (O2) was displayed to the right than to the left, whereas subtraction RTs were 19 ms faster when O2 was displayed to the left than to the right. Mathieu et al. concluded that the spatial effect was due to a shift in attention on the MNL; in particular, a rightward shift for addition problems and a leftward shift for subtraction problems.

Subsequently, Li, et al. (2018) tested Chinese participants using a priming task in which participants viewed sequentially presented simple addition and subtraction equations and their task was to verify a proposed answer orally by saying "yes" if it was correct or "no" for incorrect. The addition and subtraction equations served as a priming stimulus, and a solid white circle was the target that appeared in either the right or left hemifield after the spoken response to the arithmetic problem. Participants were instructed to respond by pressing the space bar as soon as they detected the white circle (target). Li et al. found a significant RT advantage to detect right-side targets when they were preceded by addition problems, whereas left-side targets were detected significantly faster when preceded by a subtraction problem. Li et al. attributed their results to a shift in attention on a MNL that paralleled the phenomena observed with European participants. The observation that Matheiu, et al. (2016) obtained similar spatial or directional biases in simple arithmetic for European LTR readers as Li, et al. (2018) did for Chinese participants, who traditionally read top-to-bottom (but commonly also left-to-right for English), raises the question of whether spatial effects in simple arithmetic are influenced by habitual reading patterns in the same ways as the SNARC effect (Dehaene et al., 1993; Shaki et al., 2009).

[1] Jérôme Prado confirmed (25/11/2019) that Fig. 1 in Mathieu, et al. (2016) correctly depicted the trial procedure.

The Present Experiment

The purpose of the present study was to further investigate the relationship between the SNARC effect, spatial biases in arithmetic, and habitual reading direction using the Mathieu, et al. (2016) and Shaki, et al. (2009) experimental paradigms. We tested two groups of 24 participants. One group consisted of native left-to-right readers who were tested on each task once with Arabic stimuli (i.e., 1, 2, 3…etc.) and once with written English number-word stimuli (i.e., one, two, three…etc.). The other group consisted of Pakistani and Iranian participants whose first language has a right-to-left reading direction. These participants were tested once with Arabic stimuli (i.e., 1, 2, 3…etc.) and once with Indic number stimuli (i.e., ١، ٢، ٣…etc.). The parity task was included to measure the direction of the SNARC effect in each group. If spatial factors in parity judgements and simple arithmetic are affected similarly by habitual reading direction, then we predict the following: First, we expected to see a pattern that replicated Mathieu et al. (2016, Experiment 1) results for the LTR group, whereas we expected to see a weak or a reverse spatial bias effect for the RTL group in the spatial arithmetic task (Dehaene et al., 1993; Shaki et al., 2009). In contrast, if the observed spatial bias for SNARC and arithmetic do not have a common MNL source, then we may observe that direction of bias can vary independently for the two tasks. The purpose of manipulating effects of numerical format (i.e., Arabic vs. number words) was to determine if the direction of space-related number effects depended on the format-specific habitual reading direction. Shaki et al. suggested (p. 331) that Indic number format probably was important for the Palestinian's reversed SNARC effect because only this format would be associated with right-to-left processing of numbers (see also Hung, Hung, Tzeng & Wu, 2008); however, they did not test this assumption.

Finally, given that the MNL theory has been invoked to explain both SNARC and spatial-bias effects in arithmetic, a general prediction is that spatial effects would operate similarly in both contexts. In contrast, to our knowledge, the working-memory theory of space-number interactions has not been applied explicitly to space-related phenomena in arithmetic. Nonetheless, the theory requires a numerical task to involve an ordered sequence in working memory (Abrahamse et al., 2016), as proposed for the SNARC effect (Fias & Van Dijck, 2016). The Mathieu, et al. (2016) paradigm does not seem to entail task demands that would require the generation of an ordered sequence to complete the task. As such, a working-memory based mechanism for space-number effects would not necessarily operate in the arithmetic task, which would allow spatial effects in the arithmetic and SNARC tasks in the present experiment to be relatively independent.

Method

Participants

We tested two groups of 24 participants ($n = 48$). By way of comparison, Shaki, et al. (2009) tested 12 Canadian, 16 Israeli and 11 Palestinian adult participants and Mathieu et al. (2016, Experiment 1) analyzed data from 34 French university students in their arithmetic task. For the latter, the crucial effect was the main effect of the operation on dRT (O2 left-side RT minus O2 right-side RT). For this effect, Mathieu et al. reported (p. 233) that the main effect of operation was significant with an observed $\eta^2 = 0.094$ (Cohen's $f = 0.582$). Given this effect size for the main effect in a 2×2 repeated measures ANOVA, a sample of 24 provides power of 0.76 to detect an effect of at least this magnitude (Campbell & Thompson, 2012). The 24 left-to-right (LTR) readers (21 women; mean age = 21.4) were recruited from the Dept. of Psychology participant pool at the University of Saskatchewan and they received a 2% course credit in exchange for their participation. Reported countries of origin included Canada (20), Nigeria (2), Philippines (1) and Columbia (1). Reported first language for arithmetic instruction included English (23) and Spanish (1). The 24 right-to-left (RTL) readers (10 women; mean age = 23.8 years) were recruited via advertisements posted on the University of Saskatchewan online bulletin board and received $10 in exchange for their participation. Reported countries of origin included Pakistan (13), Iran (5), Iraq (2), Saudi Arabia (2), Bangladesh (1) and Egypt (1). Reported first language for arithmetic instruction included English (17), Persian (3), Urdu (2), Farsi (1) and Arabic (1). English language proficiency requirements for admission to the University of Saskatchewan can be met various ways; for example, for the widely-used Test of English as a Foreign Language (TOEFL), an overall score of at least 86 (about 55th percentile for the undergraduate level) is required.

Experimental environment and apparatus

Participants were tested individually in a 60-min session in a quiet testing room with an experimenter present. The experimenter was fluent in English and Urdu and familiar with related languages. General instructions emphasized both response speed and accuracy. The experiment used a Microsoft Windows-based computer connected to two monitors and to a microphone through an E-prime 2.0 response box. The participant viewed a 15 inch CRT monitor and the other monitor was viewed by the experimenter. There was a chin rest centered in front of the monitor that fixed the participant's viewpoint at screen centre from a distance of about 40 cm. Stimuli were presented using E-Prime 2.0

software (Schneider, Eschman & Zuccolotto, 2012) in black against a white background. This was inadvertently different from Mathieu, et al. (2016, Experiment 1), which used white characters against a black background. An Audio-Technica ATR1200 Cardioid microphone was used to detect spoken responses to measure RT for the arithmetic task, and a standard keyboard was used to record RT for manual responses for the parity task.

Parity task

Stimuli and design

The parity task was a conceptual replication of Shaki et al. (2009). They used the Arabic digits 1, 2, 3, 4, 6, 7, 8, and 9 for their Canadian and Israeli participants and the corresponding Indic digits ۱, ۲, ۳, ۴, ۶, ۷, ۸ and ۹ for the Palestinian group. In the present study, both groups were tested with Arabic digits and the RTL group also completed the task with numbers presented in Indic digit format and the LTR group completed the task with English number words (i.e., one, two, three, three four, six, seven, eight, nine). Like English number words, Indic digits appear on currency (e.g., Pakistani rupees), page numbers, newspapers and sign boards in Arabic-language speaking regions (e.g., Iran, Pakistan) and are not typically used for written mathematical calculations. Arabic digits (1, 2, 3…) are used for that purpose in both cultural groups. Following Shaki et al., stimuli appeared in Times New Roman font size 30.

Participants received the parity task twice, once with each numerical format. For each format, the task consisted of two blocks of 80 trials separated by a short break. Each block consisted of 10 sub-blocks in which all eight numbers appeared in a random order. Counterbalancing of parity-task format order and assignment of response side to odd and even stimuli are explained in a separate section.

Procedure

Stimuli and instructions appeared on the monitor screen and participants were instructed to respond to whether a presented number was odd or even by pressing the keyboard key "A" for left-side responses and "L" for right-side responses. For each trial, a fixation dot appeared at the center of the screen for 1000 ms then flashed off for 500 ms then on for 250 ms and off for 250 ms. The single-digit stimulus then appeared at the fixation point and remained visible until a button press was detected. The fixation dot for the next trial then appeared immediately. RT was measured from the appearance of the number until the participants' keyboard response. Trial order was independently randomized for each block for each participant. There was no feedback about speed or accuracy.

Arithmetic task

Stimuli and design

The arithmetic task was a conceptual replication of Mathieu et al. (2009, Experiment 1). The small problems used the number pairs 21 31 32 41 42 43 51 52 53 54 and the larger problems included the number pairs 65 75 76 85 86 87 95 96 97 98. These were used to construct both the addition and subtraction problems. Unlike Mathieu et al. our experimental stimuli did not include zero-problems (e.g., $6+0$, $6-0$). As in the parity task, participants were tested using both Arabic digit and number word formats, Indic for RTL readers and English for LTR readers. Problems appeared in Courier New 36-point font with the larger number of the pair presented first.

For each format, the arithmetic task had four blocks within which each number pair appeared once. For the first block, a random half of the number pairs were addition problems and the other half were subtractions. For a given number pair, operation then alternated across blocks. The order of problems within each block was randomized independently for each participant. Before the first block, half of the problems in each operation were assigned randomly to the O2-left condition where O2 appeared 5° to the left of the center fixation point and the other half were assigned to the O2-right condition where O2 appeared 5° to the right of fixation. For each problem, the position of O2 then alternated across successive blocks so that each problem was tested twice with each O2 position.

Procedure

Participants were instructed to state the correct answer to each arithmetic problem in their preferred language for arithmetic. All participants answered in English. Participants received no feedback about their performance. They placed their chin on a chin rest in front of the monitor and held the microphone in their preferred hand. The trial event sequence was the same as Mathieu, et al. (2016, Experiment 1) for the 300 ms O2 ISI condition (see Fig. 1). For each trial, a central fixation dot appeared for 500 ms. O1 then appeared for 500 ms at the fixation point followed again by a central fixation point for 500 ms. The operator (+ or −) then appeared for 150 ms and was replaced by the fixation dot for 300 ms. O2 then appeared 5° off center to the left or right of the fixation dot for 150 ms followed by a blank screen up to 3000 ms. This was the maximum time allowed for the participant to answer. RT was measured from the onset of O2 and stopped when the participant's spoken response was detected by the microphone. This cleared the screen immediately, which allowed the experimenter to flag RTs as spoiled when the microphone did not detect response onset. After

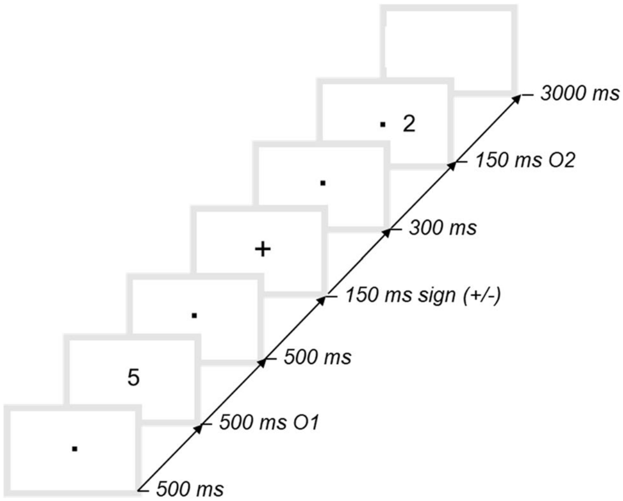

Fig. 1 Trial event sequence for the arithmetic task based on Mathieu et al. (2016, Experiment 1)

the participant's response was recorded the fixation dot for the next trial appeared.

Counterbalancing

Each participant received the parity task once with each stimulus format and the arithmetic task once in each format. The task orders (A for arithmetic and P for parity) APAP, PAPA, APPA, and PAAP were rotated through each set of four consecutive participants. Format alternated across successive tasks, with half of the participants assigned to each task order starting with Arabic and half with word format. For the first block of parity trials, odd numbered participants had odd responses assigned to the left side and even responses to the right side, whereas even numbered participants had the reverse response-side assignment. The odd–even response-side assignment was reversed for the second block of parity trials within each parity task.

Results

The Bayes Factor (BF) values reported were calculated using MorePower 6.0.4 (Campbell & Thompson, 2012). The program implements the Bayesian Information Criterion (BIC) as proposed by Masson (2011; see also Jarosz & Wiley, 2014; Nathoo & Masson, 2016; Wagenmakers, 2007), which approximates the unit-information prior as a default objective Bayes prior probability. BF_{01} denotes the odds ratio of the null (H_0) over the alternative hypothesis (H_1) and BF_{10} is the odds ratio of H_1 over H_0. The supplemental documents (https://osf.io/x5wdm/) include the E-Prime 2.0 code used for each task, and The jamovi project (2020) files containing the data and results for the main analyses reported.

Parity task

Response time

A total of 286 RTs (1.9%) were excluded from the analysis because they were more than three SD from a participant's mean RT in each Format × Response-side cell. The overall rate of incorrect answers was 4.4% (670 errors). A mixed ANOVA analysis of mean RT with group (LTR, RTL) as a between-participants factor, and within-participants' factors of format (Arabic, word), response side (left, right) and number size divided into small (1-4) vs. large (6-9) numbers.

The LTR group ($M = 635$ ms) was faster overall on the parity task compared to the RTL group ($M = 855$ ms) [$F(1, 46) = 12.40$, $p < 0.001$, MSE = 375,047, $\eta_p^2 = 0.21$, $BF_{10} = 44.4$], but this difference was larger for large numbers ($M = +246$ ms) than small numbers (M = +195 ms) [$F(1, 46) = 7.45$, $p = 0.009$, MSE = 8365, $\eta_p^2 = 0.14$, $BF_{10} = 5.30$]. Number size also interacted with format [$F(1, 46) = 7.99$, $p = 0.007$, MSE = 7719, $\eta_p^2 = 0.15$, $BF_{10} = 6.74$] because the overall 29 ms RT advantage for the small relative to large numbers was owed entirely to the word format (+55 ms) and not to Arabic format (+4 ms). This effect was further qualified by the three-way Format × Number × Group interaction [$F(1, 46) = 7.39$, $p = 0.009$, MSE = 7719, $\eta_p^2 = 0.14$, $BF_{10} = 5.15$]. This occurred because the LTR group showed no effect of number size on parity RT regardless of format (+5 and +3 ms for word and Arabic, respectively) whereas RTL readers presented a larger effect of number size with word (i.e., Indic) stimuli (+ 105 ms) than Arabic (+ 5 ms). Thus, for the RTL group, deciding the parity of large Indic numerals was relatively difficult compared to small Indic numbers, but number size had no effect on parity RT for any other Group × Format combination. This three-way effect was not anticipated, but we think it has little bearing on interpretation of the critical response-side factor.

In fact the only significant interaction with response side in the analysis of parity RT was the Side × Size interaction [$F(1, 46) = 10.78$, $p = 0.002$, MSE = 3285, $\eta_p^2 = 0.19$, $BF_{10} = 22.59$]. Small numbers were responded to 15 ms (SE = 9.1) faster with left-side responses than right-side responses, whereas large numbers were responded to 24 ms (SE = 9.7) slower with left-side than right-side responses. These results confirmed a SNARC effect. The test of the Group × Size × Side interaction, which is depicted in Fig. 2, provided evidence that the Size × Side interaction (i.e., SNARC effect in RT) did not differ between groups [$F(1, 46) = 0.064$, $p = 0.80$, MSE = 3285, $\eta_p^2 = 0.001$, $BF_{01} = 6.70$]. That said, separate ANOVAs for each group indicated that

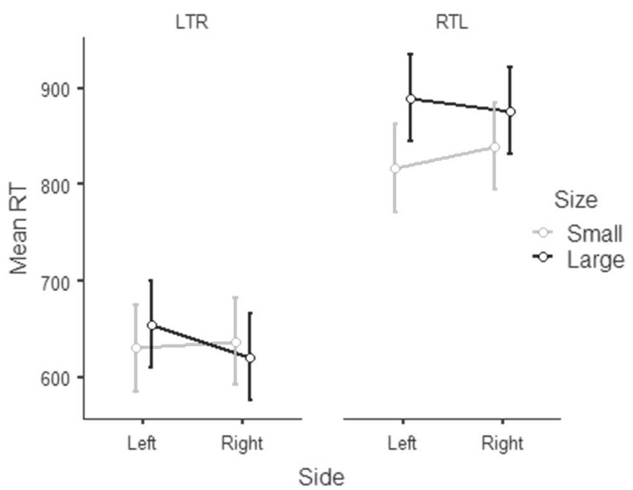

Fig. 2 Mean RT (ms) by reading-direction group, response side and number size in the parity task. Errors bars are ± 1 standard error

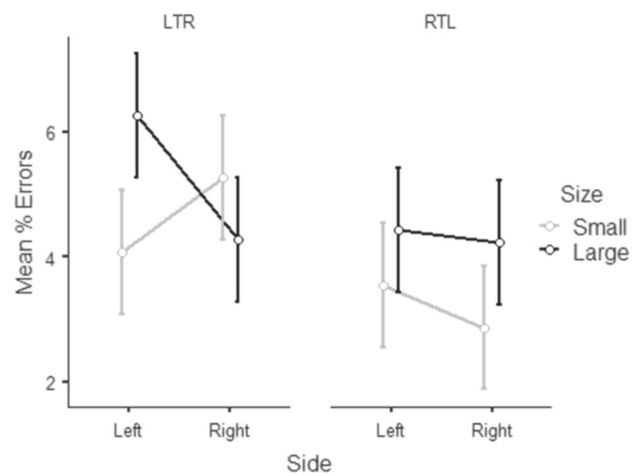

Fig. 3 Mean percentage of errors by reading-direction group, response side and number size in the parity task. Errors bars are ± 1 the standard error

the Side × Size interaction (i.e., the SNARC effect) was robust for the LTR group [$F(1, 23) = 12.47$, $p = 0.002$, $\eta_p^2 = 0.35$, $BF_{10} = 36.95$] but not for the RTL group [$F(1, 23) = 3.06$, $p = 0.09$, $\eta_p^2 = 0.12$, $BF_{01} = 1.09$]. Thus, whereas the test of the triple interaction in the standard ANOVA did not indicate group differences in the SNARC effect, the Bayes hypothesis tests strongly supported a SNARC effect only for the LTR group and not the RTL group.

In the foregoing analysis, we collapsed over the digits 1 to 4 and 6 to 9 for the small and large number conditions to increase observations per cell, but this could mask potentially larger effects for the smallest vs. the largest numbers. We repeated the analysis defining small as 1 or 2 and large as 8 or 9 (see supplemental materials), but the test of the Group × Side × Size interaction still favored no difference in the RT SNARC effect between groups [$F(1, 46) = 0.004$, $p = 0.95$, MSE = 10,036, $\eta_p^2 < 0.001$, $BF_{01} = 6.91$]. Separate group ANOVAs indicated a significant Western SNARC effect (i.e., as for the LTR group in Fig. 2) for both the LTR group [$F(1, 23) = 15.60$, $p = 0.001$, $\eta_p^2 = 0.40$] and the RTL group [$F(1, 23) = 4.36$, $p = 0.05$, $\eta_p^2 = 0.16$], but again the BF-based analysis strongly confirmed a SNARC effect in RT for the LTR group ($BF_{10} = 101.85$) but not for the RTL group ($BF_{10} = 1.64$).

Percentage of errors

A Format (Arabic, word) × Side (left, right) × Size (1–4, 6–9) × Group (LTR, RTL) ANOVA parallel to the RT analysis was conducted for percentage of errors. There was weak evidence for a main effect of size [$F(1, 46) = 4.96$, $p = 0.03$, MSE = 14.28, $\eta_p^2 = g.10$, $BF_{10} = 1.69$] such that numbers 1–4 ($M = 3.9\%$) were slightly less error prone compared to the large numbers 1–9 ($M = 4.8\%$). There was also weak evidence of a Side × Size interaction [$F(1, 46) = 4.14$, $p = 0.05$, MSE = 10.6, $\eta_p^2 = 0.08$, $BF_{10} = 1.14$].

More important was the Group × Side × Size interaction [$F(1, 46) = 7.51$, $p = 0.009$, MSE = 10.6, $\eta_p^2 = 0.14$, $BF_{10} = 5.43$] shown in Fig. 3. The LTR group presented a crossover pattern with more errors during SNARC incongruent trials (i.e., larger numbers with left-side response; smaller numbers with right-side response) relative to SNARC congruent trials [$F(1, 23) = 12.47$, $p = 0.002$, $\eta_p^2 = 0.36$, $BF_{10} = 36.94$ for the LTR Side × Size interaction]. In contrast, the RTL group's parity error rates was not affected substantively by response side [$F(1, 23) = 0.23$, $p = 0.64$, MSE = 11.54, $\eta_p^2 = 0.01$, $BF_{01} = 4.35$ for the Side × Size interaction]. A follow-up analysis that contrasted the smallest numbers 1 and 2 vs. largest numbers 8 and 9 produced the same pattern of results as the main analysis (see supplemental materials).

Taken together, the results of the parity RT and error analyses supported the Shaki et al. (2009) conclusion that there is a stronger left-to-right alignment of space and numerical magnitude for LTR readers than RTL readers.

Arithmetic task

Response time

Mathieu, et al. (2016) included problem size (small vs. large) as a factor but found that problem size had no important effects with respect to the O2 position manipulation. We similarly found no evidence that O2 position interacted with problem size (see also Campbell, Chen & Azhar, 2020); therefore, we omitted problem size in our analysis. The data and analyses with problem size as a factor are included in the supplemental materials.[2] A mixed ANOVA was conducted with group (LTR, RTL) as a between-participants factor and within-participant factors including format (Arabic, word), operation (addition, subtraction) and O2 side (left, right). A total of 397 RTs (2.6%) were excluded from the analysis either because they were more than 3 SD from a participant's mean RT in each Format × Operation × O2 side cell or marked as spoiled by the experimenter. The overall rate of incorrect answers was 5.1% (790 errors).

There was a main effect of format [$F(1, 46) = 49.59$, $p < 0.001$, MSE = 56,381, $\eta_p^2 = 0.52$, $BF_{10} = 6.07E+6$] such that mean RT was faster for the Arabic digit format ($M = 808$ ms) compared to the word formats ($M = 979$ ms). Unlike the parity task, for the arithmetic task, mean RT overall did not statistically favor the LTR group (845 ms) relative to the RTL group (942 ms) [$F(1, 46) = 2.53$, $p = 0.12$, MSE = 355,534, $\eta_p^2 = 0.052$, $BF_{01} = 1.92$]. There was, however, evidence for a Group × Side interaction [$F(1, 46) = 6.07$, $p = 0.018$, MSE = 2703, $\eta_p^2 = 0.117$, $BF_{10} = 2.82$], with the LTR group overall favoring O2 displaced to the left of center [– 14 ms, $t(23) = -2.24$, $p = 0.04$, SE = 6.42, $\eta^2 = 0.18$, $BF_{10} = 2.18$] and the RTL group nominally faster with O2 displaced rightward [12 ms, $t(23) = 1.39$, $p = 0.18$, SE = 8.45, $\eta^2 = 0.08$, $BF_{01} = 1.85$].

As Mathieu et al. (2016, Experiment 1) found, there was a large main effect of operation [$F(1, 46) = 79.03$, $p < 0.001$, MSE = 26,073, $\eta_p^2 = 0.632$, $BF_{10} = 3.82E+9$] with subtraction faster ($M = 820$ ms) than addition ($M = 967$ ms). This difference is not surprising. Mathieu et al. tested addition and subtraction problems, which we also used here, that were matched for operand pairs (e.g., 8 + 5, 8 – 5), but problem difficulty, in general, increases with the sum for addition (i.e., 13) and with the minuend for subtraction (i.e., 8; Seyler, Kirk & Ashcraft, 2003). As a result, the large addition problem set with sums > 10 were much more difficult and variable (1187 ms, SD = 50) than the large subtractions all with minuends from 6 to 9 (875 ms, SD = 34). The > 300 ms difference between large addition and large subtraction problems strongly suggests that very different processes were involved. In contrast, the small additions (822 ms, SD = 29) and small subtractions (773 ms, SD = 29) were more similar in difficulty.

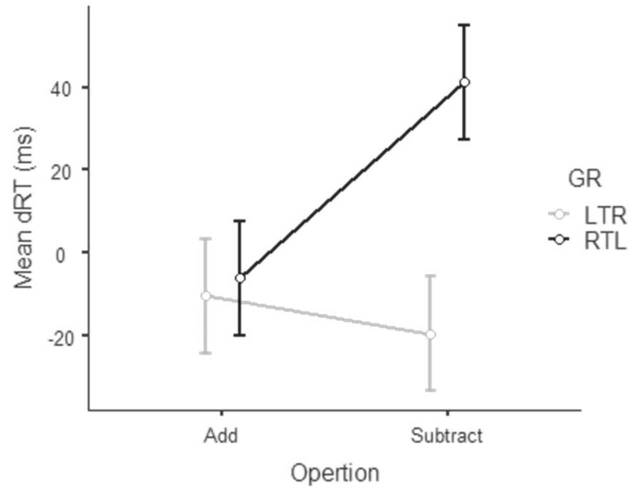

Fig. 4 Mean dRT (ms) by group and operation for small problems in the arithmetic task. $dRT = O_2$ left-side RT minus O_2 right-side RT. Error bars are ± 1 standard error

To pursue operation-specific O2 position effects we subtracted the mean RT with O2 shifted rightward from the mean RT with O2 shifted to the left to calculate dRT (Mathieu et al., 2016, p. 232).[3] For the Group × Operation × Format analysis of dRT we included only the small addition and subtraction problem sets (sum or minuend < 10), which unlike the large problem sets, were not confounded by large differences in difficulty between operations.[4] Problem format had no effects on dRT (all $p > 0.3$). Figure 4 depicts the Group × Operation interaction [$F(1, 46) = 3.95$, $p = 0.05$, MSE = 4820, $\eta_p^2 = 0.08$, $BF_{10} = 1.04$]. Per operation ANOVAs of dRT confirmed that for subtraction the RTL group had a 61 ms right-side O2 advantage compared to LTR [$F(1, 46) = 8.22$, $p = 0.006$, MSE = 10,733, $\eta_p^2 = 0.15$, $BF_{10} = 7.46$], whereas there was no group difference in mean dRT for addition [$F(1, 46) = 0.06$, $p = 0.81$, MSE = 7661, $\eta_p^2 = 0.001$, $BF_{01} = 6.73$].

More specifically, for RTL readers, subtraction dRT showed a 41 ms advantage with O2 shifted rightward [$t(23) = 2.73$, $p = 0.01$, SE = 15.10, $\eta^2 = 0.24$, $BF_{10} = 5.93$ relative to a null hypothesis of dRT = 0], whereas for addition they presented a -6 ms left-side difference [$t(23) = – 0.48$, $p = 0.64$, SE = 12.86, $\eta^2 = 0.01$, $BF_{01} = 4.35$ favoring the null hypothesis]. The 47 ms difference in mean dRT between subtraction and addition for the RTL group was significant [$t(23) = 2.42$, $p = 0.04$, SE = 19.54, $\eta^2 = 0.20$, $BF_{10} = 3.10$].

[2] The size factor in the arithmetic task participated in several interactions not related to O2 position (see supplemental materials), including an Operation × Size × Format × Group interaction) [$F(1, 46) = 9.69$, $p = 0.003$, MSE = 12,623, $\eta_p^2 = 0.17$, $BF_{10} = 14.20$]. We mention this interaction in particular because it reflected especially slow subtraction for RTL readers with larger Indic stimuli. This seems to parallel the difficulty that the RTL group had with large Indic numerals in the parity task. As this finding is not material to the O2-position manipulation we did not pursue it here.

[3] The dRT convention for the parity (i.e., SNARC) task is the opposite; that is the left-side RT is subtracted from right-side RT (e.g., Shaki et al., 2009, p. 330).

[4] There were no significant effects in the corresponding ANOVA of large problems (see the supplementary documentation).

For the LTR readers, subtraction presented a nominal – 19 ms difference favoring O2 shifted left [$t(23) = -1.32$, $p = 0.20$, SE = 14.81, $\eta^2 = 0.07$, $BF0_{01} = 2.05$] and their addition showed a nominal – 10 ms difference [$t(23) = -0.84$, $p = 0.41$, SE = 12.40, $\eta^2 = 0.03$, $BF0_{01} = 3.41$]. Mean dRT between subtraction and addition did not differ for the LTR group [$t(23) = 0.44$, $p = 0.66$, SE = 20.53, $\eta^2 = 0.008$, $BF_{01} = 4.43$].

Percentage of errors

A Format × Operation × O2 side × Group mixed factor repeated-measures ANOVA was conducted for errors. There was a main effect of operation [$F(1, 46) = 10.26$, $p = 0.002$, MSE = 34.76, $\eta_p^2 = 0.18$, $BF_{10} = 18.1$] with more addition errors ($M = 6.1\%$) than subtraction errors ($M = 4.2\%$). There was also a main effect of format [$F(1, 46) = 25.27$, $p < 0.001$, MSE = 36.48, $\eta_p^2 = 0.35$, $BF_{10} = 5.29E+3$] with more errors in word formats ($M = 6.7\%$) compared to Arabic digits ($M = 3.6\%$). There were no effects involving O2 position with all $BF_{10} < 0.37$). The analysis provided some evidence against the Group × Operation × O2 side interaction [$F(1, 46) = 1.62$, $p = 0.21$, MSE = 13.03, $\eta_p^2 = 0.03$, $BF_{01} = 3.02$], suggesting that reading direction had little or no effect on arithmetic errors in connection with O2 position.

Discussion

The purpose of the present study was to investigate the potential relationship between spatial factors in arithmetic and native reading direction using the Mathieu et al. (2016, Experiment 1) paradigm. The present study also included a parity judgement task similar to Shaki et al. (2009) to measure the SNARC effect in the same participants. It was predicted that LTR readers would demonstrate a SNARC effect reflecting a left-to-right alignment of numerical magnitude and space whereas RTL readers would demonstrate a null or reverse SNARC (Dehaene et al., 1993; Shaki et al., 2009). If spatial effects for both the parity and arithmetic tasks arise from a common mechanism, it was expected that both groups would demonstrate corresponding spatial biases during the parity and arithmetic tasks.

Parity task

The RT analysis of the parity task demonstrated an overall left-to-right oriented SNARC effect and group did not interact with response-side in the RT analysis. Nonetheless, BF values per group for the Side × Size interaction indicated that this effect was robust for LTR readers but not for the RTL group. Furthermore, the analysis of parity errors showed substantial evidence for a Side × Size × Group interaction ($BF_{10} = 5.43$). LTR readers produced a strong Side × Size interaction with more errors on small-right and large-left parity trials (i.e., incongruent trials assuming a left-to-right magnitude-space alignment) than on small-left and large-right trials. In contrast, the RTL group's parity error rates were not affected substantively by response side.

The parity error results support the Shaki, et al. (2009) conclusion that there can be a stronger left-to-right alignment of magnitude and space for LTR readers than RTL readers. It is important to note though that there was not a reverse SNARC effect for the RTL group, as was observed by Shaki et al. with their Palestinian participants. This may reflect that English as a second language is widely taught during primary school in Pakistan (the origin of the majority of our participants) and it is often the language of instruction, including for numeracy and arithmetic. Dehaene, et al. (1993) found that Iranian participants who arrived in France later in life and acquired a second language (i.e., French) later demonstrated a stronger reverse SNARC effect compared to those who arrived and acquired a second language earlier in life. Similarly, our RTL group's spatial representation of number magnitude may be a composite of their native RTL Urdu language and LTR English as a second language that tends to neutralize potential spatial influences associated with reading direction in the parity task.

Arithmetic task

The LTR group demonstrated slightly faster mean RT when O2 was displayed on the left than on the right, whereas the RTL group was nominally faster with O2 shifted leftward. This Group × Side interaction suggests that native reading direction potentially played a global role in the efficiency of scanning information in the visual display. The analyses of dRT (Fig. 4) showed a subtraction RT advantage for RTL readers with O2 shifted rightward relative to a leftward shift (BF = 7.20 relative to a 0 ms null effect), whereas for the RTL group addition there was a nominal left-side O2 RT advantage for subtraction, and both groups presented nominal left-side O2 RT advantage of addition (Fig. 4).

It is important to note that because the Mathieu et al. (2016, Experiment 1) paradigm does not include a neutral O2-position (i.e., central fixation) baseline it cannot be ruled out that there was a global directional bias of visual attention associated with native reading direction (e.g., Afsari, Ossandón, & König, 2016; Spalek & Hammad, 2005), superimposed on any operation-specific spatial biases. Indeed, as reported earlier on, the LTR group had a significant – 14 ms overall facilitation effect relative to 0 ms with O2 displayed to the left compared to the right of fixation. This is consistent with a global (i.e., operation independent) RT benefit with O2 on the left side that exploits the habitual direction of attention to the left side acquired from native LTR reading. For the RTL group, similarly, the appearance of an O2-position effect for subtraction but not addition could result from a global advantage for right-side processing by the RTL group that masks left-side facilitation for addition and exaggerates a right-side advantage for subtraction. The inability in this paradigm to assess potential global directional effects associated with reading direction makes it difficult to measure spatial biases separately for each operation. Nonetheless, the RT results for the RTL group presented the direction of operation-dependent O2 displacement effects expected according to the reading-direction hypothesis of spatial biases in number processing (Shaki et al., 2009). This effect emerged despite the participants responding in English rather than requiring their native language associated with right-to-left reading.

Space-related Effects for Parity vs. the Arithmetic Task

The results suggest that the parity task and Mathieu et al. (2016) arithmetic paradigm are sensitive to different mechanisms of spatial influences in number processing. For example, the SNARC effect in the parity task could reflect order-of-processing effects in working memory (Abrahamse et al., 2016; Fias & Van Dijck, 2016). In contrast, spatial effects in the arithmetic task may be more closely linked to visual-attentional processes that engage operation-specific spatial associations (Pinhas et al., 2015) or other spatial mechanisms intrinsic to performance (e.g., a MNL; Mathieu et al. 2016).

With respect to the parity task, the LTR group presented a robust "Western" SNARC effect in both RT and errors (Figs. 2 and 3), whereas the RTL group presented weak evidence for a Western LTR SNARC effect in the RT analysis of smallest and largest numbers (1, 2 vs. 8, 9) in the parity task. We suggest that our RTL group's ordinal mapping of number in working memory has opposing influences from their native RTL language and English as a second language that tend to neutralize effects of reading direction in the parity task.

In the arithmetic task, the LTR group presented no evidence that the position of O2 influenced performance differently between addition and subtraction (Fig. 4). Thus, spatial influences in the arithmetic task and parity task were clearly dissociated for the LTR group. Similarly, whereas RTL showed at best a weak Western SNARC effect in the parity task, in the arithmetic task they provided good evidence of an effect of O2 side that was consistent with a RTL number-space mapping (e.g., MNL). Thus, for both reading-direction groups, effects of the left vs. right side manipulation in the arithmetic or parity task did not correspond to matching effects in the other task. The results imply that the parity-based SNARC effect and side-related effects in the Mathieu, et al. (2016) arithmetic task are not equivalent or equally sensitive measures of space-related processes in cognitive number processing and likely reflect distinct origins (see also Pinhas et al., 2015).

The absence of an operation-specific effect of O2 position in the arithmetic task for the LTR group raises questions about its sensitivity for LTR readers, at least of Canadian origin. This is the third experiment (see Campbell et al., 2020) with predominantly LTR readers that did not reproduce the Mathieu et al. results (i.e., O2 right-side advantage for addition vs. left-side advantage for subtraction). This does not cast doubt on spatial effects in addition and subtraction in general, which have been demonstrated repeatedly using a variety of experimental paradigms (e.g., Blini et al., 2019; Li et al., 2018; Liu et al., 2017; Masson & Pesenti, 2014; Zhu et al., 2019). What might explain the different results in our studies and Mathieu et al. (2016)? The Mathieu et al. participants were native French speakers from the University of Lyon whereas our LTR readers were predominantly Canadians from the University of Saskatchewan. Perhaps the inconsistent results reflect different sensitivities to the Mathieu et al. O2-position manipulation across different LTR cultural groups. The present study affirmed that spatial influences in this arithmetic task can vary with cultural factors, which may extend beyond differences owing to different native reading directions (e.g., pedagogical factors).

Effects of Arabic digits vs. written number word format

Shaki, et al. (2009) tested Canadian and Israeli participants using Arabic numbers and the Palestinian participants using Indic numbers. This design assumed that spatial processing in the parity task might be determined by the opposing reading directions associated with these number formats. Here, we tested both groups with Arabic numbers and with number word stimuli, Indic numbers for the RTL group and English number words for the LTR group. The purpose was to determine if the direction of space-related number effects depended on the format-specific habitual reading direction.

Format had large effects in both the parity and arithmetic tasks. In both tasks, mean RT was much faster with Arabic format than the word formats. The superiority of Arabic digits compared to number words for number processing and calculation have been demonstrated many times (Campbell, 1994; Campbell & Alberts, 2009; Campbell & Epp, 2004; Campbell & Fugelsang, 2001). This occurs in, in part, because visual number words are rarely used for everyday quantitative tasks and are not readily encoded for these purposes. The RT analysis of the parity task indicted a Group × Format × Size interaction that occurred because RTL readers presented a larger effect of number size on parity judgments with Indic stimuli (+105 ms) than Arabic (+5 ms) whereas the LTR group showed no effect of number size for word (+5) and or Arabic numbers (+3). Thus, the RTL group found it especially difficult to extract parity from the larger Indic numbers. With respect to subtraction, the RTL group also were especially slow for large subtraction problems in Indic format ($BF_{10} = 14.2$ for the Group × Operation × Format × Size effect; see Footnote 3), perhaps mirroring their similar results with large Indic stimuli in the parity task. Neither task, however, presented evidence that spatial or side-related effects on speed or accuracy varied with the format.

Conclusions

The influence of reading direction on number processing during the parity task was robust in the error analysis, reflecting a stronger left-to-right alignment of magnitude and space for the LTR readers than the RTL readers. In the arithmetic task, the three problems elements (e.g., 3 + 4) were presented sequentially with the second operand displaced slightly to the left or right of fixation. RTL but not LTR readers presented effects of O2 position on RT that were consistent with the direction of spatial bias being linked to native reading direction. For both reading-direction groups, effects of the left vs. right side manipulations in the arithmetic or parity task did not correspond to matching effects in the other task. The results imply that parity-based SNARC effects and spatial or direction-related effects in cognitive arithmetic, at least for the Matheiu et al. (2016) paradigm, are not equivalent measures of space-related processes in cognitive number processing and likely reflect distinct functional origins.

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