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Spatial biases in mental arithmetic are independent of reading/writing habits: Evidence from French and Arabic speakers

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Abstract

The representation of numbers in human adults is linked to space. In Western cultures, small and large numbers are associated respectively with the left and right sides of space. An influential framework attributes the emergence of these spatial-numerical associations (SNAs) to cultural factors such as the direction of reading and writing, because SNAs were found to be reduced or inverted in right-to-left readers/writers (e.g., Arabic, Farsi, or Hebrew speakers). However, recent cross-cultural and animal studies cast doubt on the determining role of reading and writing directions on SNAs. In this study, we assessed this role in mental arithmetic, which requires explicit number manipulations and has revealed robust leftward or rightward biases in Western participants. We used a temporal order judgement task in French and Arabic speakers, two languages that have opposing reading/writing directions. Participants had to solve subtraction and addition problems presented auditorily while at the same time determining which of a left or right visual target appeared first on a screen. The results showed that the right target was favoured more often when solving additions than when solving subtractions both in the French- (n=31) and Arabic-speaking (n=25) groups. This was true even in Arabic-speaking participants whose preference for ordering of various series of numerical and non-numerical stimuli went from right to left (n=10). These results indicate that SNAs in mental arithmetic cannot be explained by the direction of reading/writing habits and call for a reconsideration of current models to acknowledge the pervasive role of biological factors in SNAs in adults.

Keywords: space-number association; mental arithmetic; temporal order judgement; nature-nurture

1. Introduction

One of the issues most often debated in cognitive sciences is the question of the respective influences of nature and nurture on human behaviour. This issue has received special attention in the case of numerical and arithmetic abilities. On the one hand, animals, even those very distant in human phylogenetic history, have or are able to acquire skills that allow them to process and combine numerical quantities to decide how best to act in their environment (e.g., optimizing foraging, facing or avoiding predators, etc.). Animal research has shown that chimpanzees (Boysen & Berntson, 1989; Cantlon, Merrit & Brannon, 2016), dogs (West & Young, 2002), rats (Church & Meck, 1984), domestic chicks (Rugani, Fontanari, Simoni, Regolin, & Vallortigara, 2009), or even honey-bees (Howard, Avarguès-Weber, Garcia, Greentree, & Dyer, 2019), exhibit proto-arithmetic competences (e.g., solving very simple addition and subtraction problems). Similarly, human infants are able to discriminate among small numerosities (e.g., Starkey & Cooper, 1980) or calculate the results of small problems (e.g., Wynn, 1992). On the other hand, the full range of high-level mathematical competence humans are able to develop would certainly not be reached without cultural transmission through formal learning at school. Yet, besides the general statement that at least some basic numerical competence could be inherited from nature and at least some complex mathematical competence would not be acquired without education, it is hard to assess experimentally the extent to which a specific numerical/arithmetic competence, behaviour, or mental representation, is a matter of nature, nurture, or both. One aspect of numerical cognition appears favourable to asking this question and possibly identifying the respective contributions of nature and nurture: the relationship between the processing of numbers and space, and, more specifically, this relationship in the context of arithmetic problem solving.

In the last ten years, spatial-numerical associations (hereafter, SNAs) have been revealed in arithmetic contexts, where in Western cultures subtraction appears associated with left spatial biases while addition appears associated with right spatial biases (e.g., Knops, Thirion, Hubbard, Michel, & Dehaene, 2009; Knops, Viarouge, & Dehaene, 2009; Pinhas & Fischer, 2008). Solving subtraction and addition problems facilitates the detection of left and right targets respectively (Liu, Cai, Verguts, & Chen, 2017; Liu, Verguts, Li, Ling, & Chen, 2017; Masson & Pesenti, 2014), and influences the trajectory of hand movements (Marghetis, Nunez, & Bergen, 2014; Pinheiro-Chagas, Dotan, Piazza, & Dehaene, 2017), as well as of eye movements (Hartmann, Mast, & Fischer, 2015; Masson, Letesson, & Pesenti, 2018). Converging findings show that SNAs in arithmetic are not mere epiphenomena, but that they are functionally linked to the solving procedure itself. Indeed, manipulating healthy participants' locus of attention towards the left or the right side of space impacts on their arithmetic performance (e.g., Masson & Pesenti, 2016; Masson, Pesenti, & Dormal, 2017; Mathieu, Gourjon, Couderc, Thevenot, & Prado, 2016; Wiemers, Bekkering, & Lindemann, 2014). Critically, neuropsychological studies have shown that the inability of neglect patients to orient their attention to their contralateral hemispace after brain injury differentially affects subtraction and addition: the performance of left-neglect patients was impaired when solving subtraction problems (Dormal, Schuller, Nihoul, Pesenti, & Andres, 2014), while the performance of a right-neglect patient was impaired when solving addition problems (Masson, Pesenti, Coyette, Andres, & Dormal, 2017).

The most common interpretation of SNAs in arithmetic is that solving arithmetic problems may somehow rely on a mental medium whose main spatial property is to be left-to-right oriented. Solving an arithmetical problem would require to represent the result on the left or on the right of the first operand as a function of whether the problem is a subtraction or an addition. This idea derives from the first and most extensively studied instance of SNAs, the Spatial-Numerical Association of Response Codes effect (hereafter, SNARC): when processing numbers (e.g., in classification, parity judgement, standard comparison, etc.), participants are faster in answering small numbers with a left-sided response key and large numbers with a right-sided one (Dehaene, Bossini, & Giraux, 1993; for a recent review see Cipora, Schroeder, Soltanlou, & Nuerk, 2018). This suggests a spatial compatibility between the representation of numbers in mental space and the position of answer keys in real space. While the interpretation of the exact mechanism(s) behind the SNARC effect remains a matter of debate (e.g., Gevers et al., 2010; Proctor & Cho, 2006; van Dijck & Doricchi, 2019), there is a wide consensus on the determinant role played by early directional experiences (e.g., reading direction used by parents when reading books to their children) that might influence the way children explore space. The learning of reading and of writing would in turn structure and consolidate how the spatial representation of numbers is mentally organized, and would later produce consistent SNAs in adulthood depending on reading and writing direction (for reviews, see Göbel, Shaki, & Fischer, 2011; Nuerk et al., 2015; Rugani & de Hevia, 2017; Toomarian & Hubbard, 2018). Dehaene *et al.*'s (1993) seminal study showed that the SNARC effect was weaker in Iranian participants (right-to-left readers) who had immigrated to France than in native French participants, and it was even reversed in those Iranian participants who had settled recently in France and/or had learned a

Western language later in life. Cross-cultural studies generally support this link between reading and writing habits and the SNARC effect as this effect has been reported to be inverted in Arabic speakers who have a consistent right-to-left reading and writing system for words and numerals (Shaki, Fischer, & Petrusic, 2009; Zebian, 2005; but see Cipora, Soltanlou, Reips, & Nuerk, 2019), but to be null or reduced in Hebrew and Farsi speakers who read and write words from right to left but numbers from left to right (Dehaene et al., 1993; Shaki et al., 2009; but see Zohar-Shai, Tzelgov, Karni, & Rubinsten, 2017). Other studies highlighted the plasticity of the SNARC effect on bilingual adults. For example, Russian-Hebrew bilingual participants exhibited a left-to-right SNARC effect after reading a short paragraph in Russian while the effect vanished after reading a short paragraph in Hebrew (Shaki & Fischer, 2008). In another study, Russian-Hebrew bilinguals were asked to make a parity judgement on verbal numerals that were written in Russian Cyrillic or in Hebrew. Participants showed a regular left-to-right SNARC effect with Russian verbal numerals, but no SNARC effect at all when numerals were written in Hebrew (Fischer, Shaki, & Cruise, 2009). From these findings on the SNARC effect, most current models of numerical cognition take for granted that all types of SNAs originate from a unique mental representation of numbers (e.g., Hubbard, Piazza, Pinel, & Dehaene, 2005; Fischer & Shaki, 2014). However, there is a wide variety of SNAs that might not only rely on different cognitive mechanisms but could also reveal different aspects of numerical cognition (e.g., Cipora et al., 2018; Fattorini, Pinto, Rotondaro, Doricchi, 2015; van Dijck & Doricchi, 2019). The central question of whether SNAs could stem from distinct roots has remained unaddressed so far. In the abundant literature about how culture might impact the way a mental continuum is structured and recruited to manipulate numbers, most studies focused on the

SNARC effect and overlooked whether cultural factors could impact the solving of arithmetic problems whereas it constitutes a building block of numerical cognition and a common example of explicit number manipulation. Hence, it is unknown whether the spatial associations observed in mental arithmetic stem from a mechanism similar to the SNARC effect that is supposed to be associated to reading and writing habits in adults.

While previous studies dealt with the SNARC effect as measured in number processing tasks (e.g., parity judgement, numerical comparison, etc.), the present study aims at investigating for the first time whether or not SNAs in mental arithmetic of healthy adults are shaped by reading and writing habits, taken as a proxy for early culturally-driven directional habits. We addressed this issue by comparing two groups of French (left-to-right readers/writers) and Arabic (right-to-left readers/writers) speakers with a mental arithmetic task coupled with a temporal order judgement (TOJ) task providing evidence of participants' spatial biases (Andres, Salvaggio, Lefèvre, Pesenti, & Masson, 2019; Casarotti, Michielin, Zorzi, & Umiltà, 2007; Glaser & Knops, 2020; Stelmach & Herdman, 1991). We chose to test Arabic speakers because Arabic has a consistent right-to-left reading/writing direction for both words and numbers, even when writing arithmetic problems. The task consisted in the auditory presentation of addition or subtraction problems, rapidly followed by the display of left and right targets with no or short temporal asynchronies. Participants had to solve the problem and report which target appeared first on the screen. If SNAs in mental arithmetic are related to reading/writing direction, French-speaking participants should exhibit a bias to report the right target as the first to appear after solving an addition and the left target after solving a subtraction; Arabic-speaking participants should show the reverse effect, with the right target favoured after subtraction solving and the left target after addition solving. If the direction of SNAs in mental arithmetic is not related to reading and writing habits, then both groups should show spatial biases in the same direction, with addition producing more "right target first" responses, and subtraction more "left target first" responses. As previous studies showed that the SNARC effect in bilingual individuals is modulated by the experimental set-up (Shaki & Fischer, 2008), we considered the possibility that the spatial biases induced by arithmetic operations could have changed after Arabic-speaking participants were exposed to the reading/writing habits of their host country, even for a short time. As a control, we assessed the extent to which reading/writing habits influence spatial associations in an original ordering task in which participants were asked to order numerical and non-numerical series of five items along a horizontal display. As demonstrated by previous studies, the ordering direction is related to early experience of reading/writing habits (Fuhrman & Boroditsky, 2010; Tversky, Kugelmass, & Winter, 1991). We therefore expected that French-speaking participants would classify the items from left to right while Arabic-speaking participants would classify them from right to left.

2. Methods

2.1. Participants

Thirty-one Belgian French-speaking (age range: 22-63 years; 26 females; all right-handed) and 25 Arabic-speaking (age range: 22-60 years; eight females; all right-handed; 16 from Syria; eight from Iraq; one from Palestinian territories) participants with normal or corrected-to-normal vision took part in this experiment. None declared any antecedents of mathematical learning difficulties and none was aware of the hypotheses being tested. All French-speaking participants had completed an educational curriculum of 12 to 17 years, were educated in French and had never practiced languages associated with a different direction of reading or writing. All Arabic-speaking participants had been educated in Arabic with 12 to 17 years of education, and had completed an educative curriculum for mathematics in an Arabic environment. They had migrated to a Western country in the last eight to 72 months (mean ± sd: 32±23 months), had spent limited time in Western countries, reported having received no formal teaching and very limited exposure to any left-to-right reading/writing language before they had left their country, and most of them were still living among Arabic speakers. The educative experience of mathematics of our participants was thus homogenous in terms of language use within each group. The procedures were in accordance with the ethical standards established by the Declaration of Helsinki, and the experiment was approved by the Ethics Committee of the Cliniques Universitaires Saint-Luc at the Université catholique de Louvain (Belgium).

2.2. *Task and stimuli*

The arithmetic and TOJ tasks were administrated on a Dell PC equipped with a 17-inch LCD screen and a refresh rate of 60 Hz. The task was similar to the one used in a previous study assessing spatial biases in arithmetic among French speaking participants (Andres et al., 2019). The participants were asked to perform two concurrent tasks at each trial: (i) solve an arithmetic problem (arithmetic task), and then (ii) report on which side of the screen (i.e., left or right) the first of two (a)synchronous targets appeared (TOJ task). Stimulus onset asynchrony (SOA) between the two targets could be of 0, 17, 33, 50, 100 or 200 msec. Participants had to respond aloud to a list of 2-digit ± 1-digit problems presented auditorily through headphones. The list consisted of 72 addition problems and 72 subtraction problems created on the basis of the following considerations. The first operand (O1) ranged between 11 and 79 (Addition: 11-69; Subtraction: 21-79). The second operand (O2) was either four or six. Addition and subtraction problems were matched for the magnitude of their answer (addition: 45 ± 28; subtraction: 45 ± 28), and each operation involved a carry or borrow procedure in half of the trials. The decade of the first operand, the unit of the second operand, and the carry/borrow procedures were equally counterbalanced over the different conditions of the TOJ task. The audio recording of each arithmetic problem was presented through headphones (Sennheiser PC8 USB) equipped with a microphone to record the participant's answer to the problem. Stimulus presentation and response recording were monitored using Psychopy (Peirce, 2007). The visual stimuli were an orange square and two green squares of 0.5° of visual angle, used respectively as a central fixation point and as targets presented to the left and to the right of the fixation point at 2.5° eccentricity. The participants had to indicate which of the two green squares appeared first on the screen by pressing with the index or middle finger of their dominant hand on the left or right arrow keys on a standard keyboard. We collected 6 responses for each combination of asynchronous trials (-200; -100; -50; -33; -17; 17; 33; 50; 100; 200 msec) and operation (addition *vs.* subtraction), and 12 responses for synchronous trials per operation; thus, each participant undertook 144 trials in total.

In the ordering task, a piece of paper on which five empty boxes arranged horizontally were printed was placed in front of the participants (see Figure 1). At each of the 14 trials, the participants received an instruction sheet written in their native language stating that they would receive a set of five cards with a picture on them and that they had to classify the five cards in ascending order, in the boxes, using the criterion written on the instruction sheet (e.g., their price; see Appendix for the full list of sets and items). Depending on the trial, they had to rely on magnitude (seven sets: numerical quantity of dot collection; duration of several activities; weight of animals; price of objects; age of people; speed of vehicles; football team strength), order (four sets: steps to follow to bake a cake; pictures of an apple from which bites have been taken; date of inventions of tools; date of paintings), or according to their own preference (three sets: favourite sport; favourite dish; favourite vacation location). The instructions did not specify any direction of ordering so that the task assessed the spatial orientation spontaneously adopted by the participants in each trial.

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insert Figure 1 about here

2.3. Procedure

Participants started with the arithmetic and TOJ tasks and finished with the ordering task. For the arithmetic and TOJ tasks, participants were seated 60 cm from the computer screen in a quiet room, with the midline of their face aligned with the centre of the screen and their head positioned in a chin-rest to limit movement. The sequence of events was as follows (see Figure 2). An orange fixation square was presented for 500 msec in the centre of the screen before the auditory presentation of the arithmetic problem, which lasted 1500 msec in French and 3000 msec in Arabic; duration in Arabic was longer as number-words are usually monosyllabic in French and plurisyllabic in Arabic. The fixation square disappeared 200 msec after the offset of the auditory file and the first of the two lateral green squares (i.e., the first target) was flashed for 33 msec; the second target appeared on the opposite side after the SOA. The green squares were the targets of the TOJ. Participants were asked to solve the problem first and then to respond to the TOJ within 6000 msec. Responses to the arithmetic problems were written down by the experimenter.

Responses to the TOJ were made on a standard keyboard on which participants had to press left or right keys with their right index finger and middle finger, respectively. The task was composed of one unanalysed training block of 12 trials, and three experimental blocks of 48 trials in randomized order. For the ordering task, the participants had to read aloud the instruction sheet to discover the classification rule of the series. Cards were shuffled by the experimenter and given one by one to the participant who had to immediately say aloud what was represented on the card and wait to receive the five cards before classifying them. A session lasted approximately 60 minutes. All communications with the participants were made in their mother tongue by a French or Arabic speaker depending on the group, be it for oral and written instructions, consent forms, and stimuli presentation.

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insert Figure 2 about here

2.4. Data analysis

In the arithmetic task, a generalized linear mixed model (GLMM) was used on the data of all the participants (Arabic speaker n=25 and French speaker n = 31) to model the error rates (ER) with Operation (Addition *vs.* Subtraction) and Group (Arabic *vs.* French speakers) as fixed effect and the differences between participants as a random intercept. In the TOJ, trials in which participants gave an incorrect answer or did not respond within the 6000 msec were discarded from the analyses. The TOJ analysis was thus performed on the trials where a correct arithmetic answer was given in the prescribed delay. A GLMM was used to model the probability of responding "right target first" with SOA (logistic function), Operation and Group and their interaction as fixed effects, and the differences between participants as a random intercept and the combination of participants and operation as a random slope. A GLMM analysis is especially indicated in the present case since arithmetical performance could vary across participants: the GLMM outperforms methods that give an equal weight to all the observations as the differences between participants are modelled as a random effect; hence, the GLMM takes into account the differences in the number of trials per condition, which varied as a function of the arithmetic performance of each participant. The SOA was expressed as a negative value (from -200 to -17 ms) when the first target was on the left, as a positive value (from 17 to 200 ms) when the first target was on the right and set at 0 when the targets were simultaneous. The points of maximal uncertainty (PMU), corresponding to the estimated SOA where participants gave an equal proportion of rightward and leftward responses, were obtained from the intercept (B0) and the slope (B1) revealed by the GLMM using the formula $-\frac{B0 * \text{OPERATION}}{B1}$.

Due to time constraints during some testing sessions, the ordering task could only be administered to 17 out of the 25 Arabic speakers who participated in the study. In the ordering task, each trial was coded as left-to-right (L-R) ordering or right-to-left (R-L) ordering depending on the direction used by the participant to order the cards. We then calculated the proportion of R-L ordering for each participant and compared the proportion of R-L ordering per participant between groups. Participants were categorized into L-R or R-L sorters if they classified more than 60% of the trials as such, and as non-directional sorters (N-D) if no preferred direction emerged (i.e., 41 to 59% of L-R/R-L trials). A chi-square analysis was then used to assess whether the proportion of R-L, L-R and N-D sorters was (dis)similar in Arabic- (n=17) and French-speakers (n=31).

3. Results

3.1. Ordering task

All the tested participants were able to identify flawlessly the concepts represented on the cards. In the French-speaking sample, 86±24% of the trials were ordered from left to right, which was significantly higher than the percentage of trials ordered from left to right in the Arabic-speaking group (45±35%; $t(46)=4.931$, $p<.001$). Based on individual performance, 29 out of the 31 (93%) French speakers and six out of 17 (35%) Arabic speakers were classified as L-R sorters. Two out of the 31 (6.5%) French speakers and 10 out of the 17 (59%) Arabic speakers were classified as R-L sorters. One remaining Arabic speaker (6.5%) was classified as N-D sorters. *Chi*-square analysis showed that the proportions of R-L, L-R, and N-D sorters were significantly different in the two samples ($\chi 2$ (2, 48) = 18.979, p < .001, Phi = .629). Figure 3 shows that the percentage of participants exhibiting a right-to-left ordering strategy was higher in Arabic speakers than in French speakers and vice versa for the left-to-right ordering strategy.

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insert Figure 3 about here

3.2. Arithmetic task

For three participants, the last block of the TOJ task was not correctly recorded and data of this last block were not included in the analysis. In the arithmetic task, the GLMM on accuracy showed a significant main effect of Operation ($F(1,7916)=61.686$, $p<.001$) indicating that participants were more accurate for additions (95%) than for subtractions (90%). There was a significant main effect of Group ($F(1,7916)=8.414$, $p=.004$) indicating that French-speaking participants (95%) were more accurate than Arabic-speaking participants (90%). There was also a significant Operation by Group interaction (*F*(1,7916)=6.156, *p*=.013) revealing that French-speaking participants (93%) performed better than Arabic-speaking participants (86%; *t*(7916)=3.447, *p*=.002) in subtraction while there was no difference between groups in addition (French speakers: 96%, Arabic speakers: 94%; *t*(7916)=1.654, *p*=.196; all *t*-tests used Bonferroni correction for multiple comparisons).

3.3. TOJ task

In the TOJ task, the GLMM showed a significant main effect of SOA (*F*(1,7227)=948.24, *p*<.001) indicating that the probability of answering "right target first" increased from approximately 8% at SOA -200 msec to 91% at SOA +200 msec, and a main effect of Operation (*F*(1,7227)=15.125, *p*<.001) indicating that the probability of answering "right target first" was higher for addition than for subtraction trials (see Table 1). There was a significant interaction between SOA and Operation (*F*(1,7227)=7.767, *p*=.005) that was included in a significant three-way interaction with Group (*F*(1,7227)=10.999, *p*=.001). Comparisons (α=.05 corrected for multiple SOAs) showed that, in French-speaking participants, the probability of reporting the right target was significantly higher after addition than subtraction for SOAs ranging from -50 msec to +33 msec (mean difference of 6.16%), whereas in Arabic-speaking participants, the probability of reporting the right target was significantly higher after addition than subtraction for SOAs ranging from +17 msec to +200 msec (mean difference of 8%; see Table 2 and Figure 4). These results show that, in both groups, addition increases the probability of "right target first" responses compared to subtraction. The GLMM revealed no other main effect or interaction (all *p*-values > .4). The PMU was -1 msec for addition and +22 msec for subtraction for the French group and of -5 msec for addition and +10 msec for subtraction for the Arabic group.

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insert Tables 1 and 2 and Figure 4 about here

3.4. Complementary analyses in R-L Arabic-speakers

Our results suggest that SNAs in mental arithmetic are oriented in the same direction whatever the cultural reading/writing habits. However, passive exposure to the reading/writing direction of the host country might have blurred the results of the previous analysis and masked right-to-left SNAs exhibited by some Arabic speakers. We thus tested whether the time spent by Arabic speakers in a Western country (expressed in month) would impact the results, with the assumption that if SNAs in mental arithmetic are related to reading/writing direction, the participants that spent less time in a Western country might more likely exhibit a right-to-left SNA congruent with the right-to-left reading/writing direction of Arabic language. We thus ran a GLMM with SOA (logistic function), Operation (Addition vs. Subtraction), and Time spent in Western countries (expressed in months), and their interactions as fixed effects, the combination of participants and Operation as a random slope, and the differences between participants as a random intercept on the TOJ task. The results were consistent with the main analysis. They revealed a significant main effect of SOA ($F(1,3053)=154.834$, $p<.001$) showing the same trend as in the whole group, and an interaction between SOA and Operation ($F(1,3053)=7.807$, $p=.005$), indicating that the probability of reporting the right target as the first was significantly higher after addition than subtraction for all SOAs ranging from +33 msec to +200 msec. Crucially, Time did not interact significantly with Operation ($F(1,3053)=2.096$, $p=.148$), and the triple interaction was far from significance ($F(1,3053)=.756$, $p=.385$). No other significant main effect or interaction reached significance (all p-values >.1). The PMU was -5 msec for addition and +10 msec for subtraction.

We conducted a second complementary analysis based on the direction of the ordering pattern to test whether including Arabic speakers with a L-R ordering bias might have masked SNAs congruent to the cultural reading/writing habits in the TOJ. We thus used a GLMM to model the probability of responding “right target first” with SOA (logistic function), Operation (Addition vs. Subtraction), and their interactions as fixed effects, and the differences between participants as a random intercept on the TOJ task with only the 10 Arabic-speaking R-L sorters, on the assumption that these participants were the least influenced by their new Western environment, irrespective of the time spent in a Western country. If exposure to a new culture is related to SNAs in mental arithmetic, then the sub-sample of participants with a R-L behaviour congruent with their native reading/writing habits should demonstrate a rightward bias in response to subtraction compared to addition. However, this was not the case: the GLMM conducted in this subsample of participants still revealed a significant main effect of SOA ($F(1,1207)=170.269$, $p<.001$) showing the same trend as in the whole group, a main effect of Operation ($F(1,1207)=6.894$, $p=.009$) indicating that Arabic-speaking R-L sorters also favoured the right target after an addition and the left target after a subtraction, and an interaction between SOA and Operation ($F(1,1207)=4.727$, $p=.03$), indicating that the probability of reporting the right target as the first was significantly higher after addition than subtraction for all SOAs ranging from +17 msec to +100 msec. The PMU was -15 msec for addition and +12 msec for subtraction.

4. Discussion

It is generally assumed that the orientation of SNAs in healthy adults is (re-)shaped by cultural directional habits. Yet, as SNAs in arithmetic have so far only been reported in participants reading and writing from left to right (e.g., Marghetis et al., 2014; Masson et al., 2017; Mathieu et al., 2016), whether or not they derive from these cultural habits, as other SNAs possibly do, remains an open question. In this study, we tested if cultural reading/writing habits built and consolidated through early educational experiences drive SNAs in addition and subtraction. To do so, we tested adult participants with opposite reading/writing directions in a TOJ task coupled with an arithmetic solving task to reveal the spatial biases induced by addition and subtraction. To assess spatial associations non-related to arithmetical operations, we asked the same participants to sort various series of cards, and noted if they spontaneously used a L-R or a R-L sorting alignment.

In the arithmetical task, accuracy ranged from 86% to 96% and was slightly higher for addition than subtraction, a result classically observed with the kind of multi-digit problems used here. Moreover, French-speaking participants turned out to perform slightly better than Arabic-speaking participants in subtraction, while no such difference between groups was observed for addition. Globally, the very good arithmetical performance shows that the participants did perform this task carefully.

In the TOJ task, SOAs modulated the probabilities to answer that the right/left target appeared first: as one might have expected, the larger the SOAs, the easier the detection of the asynchrony between the two targets, and the higher the probability to answer "right/left target first". Here again, this result shows that the participants performed this task carefully. The main result, though, was the 3-way interaction revealing that the probability to answer "right/left target first" was modulated not only by SOAs, but also by the operation and the group. Indeed, participants answered more often "right target first" for addition than for subtraction, and this was true in both groups at similar and different SOAs. In the French-speaking participants, the difference was of about 6% for SOAs ranging from -50 to

+33 msec; in Arabic-speaking participants, the difference was 8% in average for SOAs from +17 to +200 msec. Thus, besides the significant difference between operations going in the same direction in both groups at overlapping SOAs (i.e., +17 and +33 msec), there was also an operation effect observed at negative SOAs in the French-speaking group and at positive SOAs in the Arabic-speaking group. Worthy of noting, the spatial bias went in the same direction in the two groups, the difference between groups concerning only the range of SOAs where this bias appeared.

We suggest that the difference in the SOAs where the operation effect is observed across groups may reflect a combined effect of biases coming, on the one hand, from the arithmetic operations and, on the other hand, from the natural tendency of healthy human beings to attend preferentially the left *vs.* right side of space. Named *pseudoneglect* (Bowers & Heilman, 1980), this natural bias may differ across cultures. It is usually more pronounced towards the left in left-to-right readers/writers than in right-to-left readers/writers as observed in several tasks involving spatial processing (e.g., line bisection: Rinaldi, Di Luca, Henik, & Girelli, 2014; inhibition of return: Spalek & Hammad, 2005). Another study using the TOJ showed that pseudoneglect was attenuated in Arabic speakers when compared to Spanish speakers (Pérez, Garcia, Valdès-Sosa, & Jaskowski, 2011). In the present study, the combined effect of a leftward bias (i.e., "western" pseudoneglect) and subtraction would make the difference between targets even easier to detect for SOAs that favour the detection of the left target in the French-speaking participants, while the combined effect of rightward bias (i.e., "eastern" pseudoneglect) and addition would make the difference between targets even easier to detect for SOAs that favour the detection of the right target in the Arabic-speaking participants. Speculating about when and how the effects of pseudoneglect and operations combine goes beyond the scope of the present study. The main point here is that the difference between groups concerns only the level of uncertainty (i.e., the SOAs) under which the spatial bias is observed and not its direction, as the same direction is actually reflected by addition and subtraction biases.

Interestingly, the absence of influence of reading/writing habits on the orientation of spatial biases observed in mental arithmetic dissociates from the influence of reading/writing habits on the spatial biases observed in spontaneous card ordering. Whereas French speakers sorted series of cards from left to right almost exclusively, about 60% of the Arabic speakers used a right-to-left alignment consistent with their reading/writing direction. This shows that the Arabic speakers, as a group, behave differently than French speakers. Reading/writing direction was also found to affect space-order associations in tasks that require participants to memorize random sequences of colour patches presented sequentially at the centre of the screen and then determine whether a probe was or was not part of the memorized sequence by pressing right or left keys (Guida et al., 2018). In our study, we observed that the sorting strategy was more consistent in French than in Arabic speakers. This fits with previous studies indicating that the left-to-right preference for arranging temporal sequences is actually more consistent for English participants than the right-to-left preference of Arabic and Hebrew speakers (Tversky et al., 1991). Within the Arabic sample, the left-to-right arithmetical bias was observed even in those participants exhibiting a R-L alignment when sorting a series of pictures. While the way these Arabic speakers sorted cards was congruent with the spatial orientation imposed by their mother tongue, the SNAs induced by solving arithmetic problems was incongruent with the spatial orientation imposed by their mother tongue. This finding suggests that the arithmetical spatial biases were not simply reversed with exposure to the left-to-right reading environment after they had arrived in western countries. Several observations led us to consider the card sorting task as a more explicit and more adequate measure of spatial associations compared to SNARC-like tasks. First, research has shown that the SNARC effect is highly flexible and varies as a function of task, range, experimental set-up, etc. (e.g., Brigadoi, Basso Moro, Falchi, Cutini, & Dell'Acqua, 2018; Fattorini et al., 2015). Second, a recent bootstrap analysis of more than 1000 participants in 18 different SNARC-like data sets has shown that the SNARC effect is in fact driven by a minority of individuals (≤ 45%) who reveal the effect beyond measurement error (Cipora et al., 2019). Third, recent findings cast some doubt on the popular belief that the SNARC effect is inverted in right-to-left readers/writers (see below). Given these interindividual variability and uncertainty on the real significance of the SNARC measurement, we believe that using another proxy for reading/writing-related biases was more appropriate.

The Iranian participants tested by Dehaene and colleagues (1993) in their seminal SNARC study had learned a Western language before age 20, had been in France for up to 12 years, and were mostly university students frequently exposed to French. In comparison, all Arabic-speaking participants of the present study were born and educated in Syria, Iraq or Palestinian territories, had received almost no formal teaching to Western languages before immigrating to Europe, had been in Europe for less than six years and about half of them for less than two years. At the time of the testing, they were spending most of their time among other Arabic speakers, and were still reading and writing in Arabic on a daily basis. Importantly, the duration of their exposure to Western culture expressed by the time spent in Western countries had no impact on the orientation of the SNAs in mental arithmetic measured in the TOJ, showing consistent and robust left-to-right SNAs among the Arabic participants.

This complementary analysis thus rules out the possibility that participants who were less exposed to Western culture would show right-to-left SNAs in mental arithmetic. Altogether, the time our participants spent in Western counties, their linguistic background, and their persistent tendency to order non-numerical series from right to left all strongly support the idea that their responses in the TOJ task were not merely driven by exposure to Western languages.

Some studies emphasized the influence of the linguistic context of the experiment, namely the language used to give the instructions and test the participants, on the orientation of the SNARC effect (e.g., Shaki, & Fischer, 2008; Hung, Hung, Tzeng, & Wu, 2008). Our results showing robust left-to-right SNAs in mental arithmetic are incompatible with the idea of these SNAs being flexibly modulated by the linguistic context of the experiment and/or of the background of the participants. Indeed, in the present study, all written forms, instructions and testing material were presented in Arabic to the Arabic speakers, and the experimenters in charge of collecting the data in this group were fluent in Arabic and instructed not to use English or French during the whole session. If SNAs in mental arithmetic were flexible and simply influenced by the experimental context, then the directionality of the language system used during data collection should have switched back to right-to-left SNAs compatible with the Arabic written system; this was not the case. The dissociation between the SNAs observed in the Arabic sample, their reading/writing habits, and their ordering preference undermine the idea that reading/writing habits determine the orientation of SNAs in mental arithmetic.

We argue against the commonly accepted view that reading/writing habits play a decisive and exclusive role in shaping SNAs, a view refuted by our data in mental arithmetic. Concerning the long-lasting idea of a culturally-dependent SNARC effect, recent studies conducted in Hebrew or Farsi speakers reported a left-to-right SNARC effect, opposite to their writing/reading direction, which casts some doubt on the fundamental impact of this cultural factor (Hebrew: Zohar-Shai, et al., 2017; Farsi: Mazhari, Shahrbabaki, Pourrahimi, Faezi, & Baneshi, 2019; for similar left-to-right SNARC effect in a subsample of Arabic speakers from data collected online, see also Cipora, et al., 2019). An alternative account suggests that biological traits inherited from animals could determine the direction of spatial biases in numerical processing (Rugani, 2018; Vallortigara, 2018). Indeed, there is evidence showing that preverbal human infants (e.g., Bulf, de Hevia, Macchi Cassia, 2016; de Hevia, Izard, Coubart, Spelke, & Streri, 2014; de Hevia, Veggiotti, Streri, & Bonn, 2017; Patro & Haman, 2012) and animals (e.g., Adachi, 2014; Drucker & Brannon, 2014; Gazes et al., 2017; Johnson-Ulrich & Vonk, 2018; Rugani, Vallortigara, Priftis, & Regolin, 2015) exhibit left-to-right SNAs. Hemispheric brain asymmetries may be responsible for the direction of SNAs (e.g., de Hevia, Girelli, & Macchi Cassia, 2012; Rugani, Vallortigara, & Regolin, 2015). Since the right hemisphere is dominant in visuo-spatial attention, attention is biased towards the left hemifield (Corbetta & Shulman, 2011). This pseudoneglect is observed in humans (Bowers & Heilman, 1980) and animals (Diekamp, Manns, Güntürkün, Vallortigara, & Regolin, 2005), and would make them more likely to start scanning collections of objects from the left to the right in order to count them or to estimate numerosities. In object counting tasks, numerosity is often confounded with order: numerosity estimates increase as the count progresses from the first to the last items. Assuming object counting is related to the scanning direction imposed by a left-biased attention system, small numerosities (i.e., the first items processed) would become associated with the left side of space while large numerosities (i.e., the last items) would be associated with the right side of space. As a result, adding objects to a collection would be biased to the right side of space compared to subtracting objects. Recently, Vallortigara (2018) also suggested that SNAs in non-verbal beings might be related to emotional valence. The anterior regions of the left and right hemispheres are related to approach and withdrawal processes, which are themselves associated with positive and negative emotions respectively (Davidson, 2004). If larger/smaller numerical magnitudes are associated with better/worse and more/less approachable stimuli, they would activate the left/right hemisphere to a different extent. The increased activation of one hemisphere, as triggered by the emotional valence of large or small numerosities, would promote a deviation of attention towards the contralateral hemifield. Similar relationships might occur when animals are confronted with situations where numerosities are decreasing or increasing and these might ground the SNAs in mental arithmetic in humans. Whether and how brain asymmetries are responsible for SNAs and ordering patterns requires deeper investigation. We suggest that ordering series, irrespective of their contents, be it related to some semantic or affective knowledge (e.g., historic events, personal preferences, scripts), is more strongly influenced by cultural habits than arithmetical problem solving, presumably because such sorting task is unlikely to be supported by pre-existing systems shared with animals, but rather needs to be acquired through education and cultural transmission. In other words, displaying preferences for various items on a spatial medium would greatly depend on the way we interacted with others in a specific culture (e.g., board games) or on the way we learned these events through handbooks (e.g., timelines) because education and social exchanges are the only source of knowledge. Conversely, arithmetic capacities most likely built on innate systems are shared with other species and dedicated to keeping track of quantities in a changing environment (e.g., Church & Meck, 1984; Rugani, et al., 2009).

The present findings have strong implications for current knowledge about numerical processing as they temper the importance given to reading/writing habits on number processing by the most influential recent theoretical framework. Current models of human numerical cognition admit the existence of biological traits that could set a left-to-right orientation of spatial biases in the early steps of life, but they suggest this default orientation would be progressively and automatically consolidated (e.g., in Western cultures) or over-written (e.g., in Arabic cultures) across development and education to fit with the direction of cultural habits (e.g., Cipora et al., 2018; Göbel, McCrink, Fischer, & Shaki, 2018; McCrink & Opfer, 2014; McCrink, Caldera, & Shaki, 2017; Nuerk et al., 2015; Patro, Nuerk, & Cress, 2016; Rugani & de Hevia 2017; Toomarian & Hubbard, 2018). Our results show that, at least in the context of arithmetical problem solving, left-to-right biologically-rooted associations between arithmetical operations and space remains unchanged by education and cultural experiences in human adults. Further research should now test whether the proto-arithmetic capacities exhibited by animals and preliterate children (e.g., Howard, et al., 2019; Rugani, et al., 2009) will trigger left-to-right spatial biases similar to those observed in human adults when calculating. Investigating SNAs related to the concepts of adding or withdrawing numerosities in non-human species or newborn humans would be an optimal approach to untangling the cultural or biological account of SNAs, and their developmental and evolutionary trajectory. Another challenging issue is to understand the reasons why some explicit spatial behaviours, such as those measured in our ordering task, seem to follow cultural reading/writing habits whereas SNAs in mental arithmetic do not.

5. Conclusion

This study shows for the first time that the spatial biases related to addition and subtraction solving are oriented in a L-R direction whatever the cultural reading/writing habits of French- and Arabic-speaking participants. Our results thus contradict the most influential framework in numerical cognition, which states that all types of SNAs in human adults are determined by directional cultural habits (i.e., reading/writing direction). The origin of these spatial biases in mental arithmetic remains an open question that requires further investigation in humans and animals, but our finding indicates that identifying the roots of SNAs in numerical processing is clearly more complex than previously thought and these roots cannot be reduced to reading/writing direction.

Author contributions

Nicolas Masson: Conceptualization; Methodology; Investigation; Formal analysis; Data Curation; Writing - Original Draft; Writing - Review & Editing; Visualization; Project administration

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References

Adachi, I. (2014). Spontaneous spatial mapping of learned sequence in chimpanzees: evidence for a SNARC-like effect. *PLoS One, 9*(3), e90373. https://doi.org/10.1371/journal.pone.0090373

Andres, M., Salvaggio, S., Lefèvre, N., Pesenti, M., & Masson, N. (2019). Semantic interactions between arithmetic and space in the early stages of problem processing. *Memory & Cognition*. doi: 10.3758/s13421-019-00975-9

Bowers, D., & Heilman, K. M. (1980). Pseudoneglect: Effects of hemispace on a tactile line bisection task. *Neuropsychologia, 18*(4-5), 491-498. https://doi.org/10.1016/0028-3932(80)90151-7

Boysen, S. T., & Berntson, G. G. (1989). Numerical competence in a chimpanzee (Pan troglodytes). *Journal of Comparative Psychology, 103*(1), 23. http://dx.doi.org/10.1037/0735-7036.103.1.23

Brigadoi, S., Basso Moro, S., Falchi, R., Cutini, S., & Dell'Acqua, R. (2018). On pacing trials while scanning brain hemodynamics: The case of the SNARC effect. *Psychonomic Bulletin & Review, 1–7*. https://doi.org/10.3758/s13423-017-1418-1

Bulf, H., de Hevia, M.D., & Macchi Cassia, V. (2016). Small on the left, large on the right: Numbers orient visual attention onto space in preverbal infants. *Developmental Science, 19*(3), 394-401. https://doi.org/10.1111/desc.12315

Cantlon, J.F., Merrit, D.J., & Brannon E.M. (2016). Monkeys display classic signatures of human symbolic arithmetic. *Animal cognition, 19*, 405-415. https://doi.org/10.1007/s10071-015-0942-5

Casarotti, M., Michielin, M., Zorzi, M., & Umiltà, C. (2007). Temporal order judgment reveals how number magnitude affects visuospatial attention. *Cognition, 102*, 101-117. https://doi.org/10.1016/j.cognition.2006.09.001

Church, R.M., & Meck, W.H (1984). The numerical attribute of stimuli. *In* H.L. Roitblat, T.G. Bever, & H.S. Terrace (Eds.), *Animal cognition*. Hilsdale, NJ: Erlbaum, pp. 445-464.

Cipora, K., Schroeder, P. A., Soltanlou, M., & Nuerk, H.-C. (2018). More space, better math: Is space a powerful tool or a cornerstone for understanding arithmetic? In K. S. Mix & M. T. Battista (Eds.), *Visualizing Mathematics: The Role of Spatial Reasoning in Mathematical Thought*. Springer Nature.

Cipora, K., Soltanlou, M., Reips, U, -D., & Nuerk, H.-C. (2019). The SNARC and MARC effects measured online: Large-scale assessment methods in flexible cognitive effects. *Behavior Research Methods*, 1-17. Doi:10.3758/s13428-019-01213-5

Cipora, K., van Dijck, J.-P., Georges, C., Masson, N., Goebel, S., Willmes, K., M. Pesenti, C. Schiltz, Nuerk, H.-C. (2019). A Minority pulls the sample mean: on the individual prevalence of robust group-level cognitive phenomena–the instance of the SNARC effect, Preprint on https://psyarxiv.com/bwyr3/

Corbetta, M., & Shulman, G. L. (2011). Spatial neglect and attention networks. *Annual Review of Neuroscience, 34*, 569-599. https://doi.org/10.1146/annurev-neuro-061010-113731

Davidson, R. J. (2004). Well–being and affective style: neural substrates and biobehavioural correlates. *Philosophical Transactions of the Royal Society of*

London. Series B: Biological Sciences, 359(1449), 1395-1411. https://doi.org/10.1098/rstb.2004.1510

de Hevia, M. D., Girelli, L., & Macchi Cassia, V. (2012). Minds without language represent number through space: origins of the mental number line. *Frontiers in Psychology, 3*, 466. https://doi.org/10.3389/fpsyg.2012.00466

de Hevia, M. D., Izard, V., Coubart, A., Spelke, E. S., & Streri, A. (2014). Representations of space, time, and number in neonates. *Proceedings of the National Academy of Sciences, 111*(13), 4809-4813. https://doi.org/10.1073/pnas.1323628111

de Hevia, M. D., Veggiotti, L., Streri, A., & Bonn, C. D. (2017). At Birth, Humans Associate "Few" with Left and "Many" with Right. *Current Biology, 27*(24), 3879-3884. https://doi.org/10.1016/j.cub.2017.11.024

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology-General, 122*, 371-396. doi: 10.1037/0096-3445.122.3.371

Diekamp, B., Manns, M., Güntürkün, O., Vallortigara, G., & Regolin, L. (2005). Line bisection error and pseudoneglect in birds. *Journal of Psychophysiology, 19*, 154.

Dormal, V., Schuller, A. M., Nihoul, J., Pesenti, M., & Andres, M. (2014). Causal role of spatial attention in arithmetic problem solving: Evidence from left unilateral neglect. *Neuropsychologia, 60*, 1–9. http://dx.doi.org/10.1016/j.neuropsychologia.2014.05.007

Drucker, C. B., & Brannon, E. M. (2014). Rhesus monkeys (Macaca mulatta) map number onto space. *Cognition, 132*(1), 57-67. https://doi.org/10.1016/j.cognition.2014.03.011

Fattorini E, Pinto M, Rotondaro F, Doricchi F (2015) Perceiving numbers does not cause automatic shifts of spatial attention. *Cortex, 73*, 298–316. https://doi.org/10.1016/j.cortex.2015.09.007

Fischer, M. H., & Shaki, S. (2014). Spatial associations in numerical cognition—From single digits to arithmetic. *The Quarterly Journal of Experimental Psychology, 67*(8), 1461-1483. https://doi.org/10.1080/17470218.2014.927515

Fischer, M. H., Shaki, S., & Cruise, A. (2009). It takes just one word to quash a SNARC. *Experimental Psychology, 56(*5), 361. DOI: 10.1027/1618-3169.56.5.361

Fuhrman, O., & Boroditsky, L. (2010). Cross-cultural differences in mental representations of time: Evidence from an implicit nonlinguistic task. *Cognitive Science, 34*(8), 1430-1451. https://doi.org/10.1111/j.1551-6709.2010.01105.x

Gazes, R. P., Diamond, R. F., Hope, J. M., Caillaud, D., Stoinski, T. S., & Hampton, R. R. (2017). Spatial representation of magnitude in gorillas and orangutans. *Cognition, 168*, 312-319. https://doi.org/10.1016/j.cognition.2017.07.010

Gevers, W., Santens, S., Dhooge, E., Chen, Q., Van den Bossche, L., Fias, W., & Verguts, T. (2010). Verbal-spatial and visuospatial coding of number–space interactions. *Journal of Experimental Psychology: General, 139*(1), 180. http://dx.doi.org/10.1037/a0017688

Glaser, M., & Knops, A. (2020). When adding is right: Temporal order judgements reveal spatial attention shifts during two-digit mental arithmetic. *Quarterly Journal of Experimental Psychology*. https://doi.org/10.1177/1747021820902917

Göbel, S. M., McCrink, K., Fischer, M. H., & Shaki, S. (2018). Observation of directional storybook reading influences young children's counting direction. *Journal of Experimental Child Psychology, 166*, 49-66. https://doi.org/10.1016/j.jecp.2017.08.001

Göbel, S. M., Shaki, S., & Fischer, M. H. (2011). The cultural number line: a review of cultural and linguistic influences on the development of number processing. *Journal of Cross-Cultural Psychology, 42*(4), 543-565. https://doi.org/10.1177/0022022111406251

Guida, A., Megreya, A. M., Lavielle-Guida, M., Noël, Y., Mathy, F., van Dijck, J. P., & Abrahamse, E. (2018). Spatialization in working memory is related to literacy and reading direction: Culture "literarily" directs our thoughts. *Cognition, 175*, 96-100. https://doi.org/10.1016/j.cognition.2018.02.013

Hartmann, M., Mast, F. W., & Fischer, M. H. (2015). Spatial biases during mental arithmetic: Evidence from eye movements on a blank screen. *Frontiers in Psychology, 6,* 12. http://dx.doi.org/10.3389/fpsyg.2015.00012

Howard, S. R., Avarguès-Weber, A., Garcia, J. E., Greentree, A. D., & Dyer, A. G. (2019). Numerical cognition in honeybees enables addition and subtraction. *Science Advances, 5*(2), eaav0961. DOI: 10.1126/sciadv.aav0961

Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number and space in parietal cortex. *Nature Reviews Neuroscience, 6*(6), 435-448. doi:10.1038/nrn1684

Hung, Y. H., Hung, D. L., Tzeng, O. J. L., & Wu, D. H. (2008). Flexible spatial mapping of different notations of numbers in Chinese readers. *Cognition, 106*(3), 1441-1450. https://doi.org/10.1016/j.cognition.2007.04.017

Johnson-Ulrich, Z., & Vonk, J. (2018). Spatial representation of magnitude in humans (Homo sapiens), Western lowland gorillas (Gorilla gorilla gorilla), and American black bears (Ursus americanus). *Animal Cognition*, 1-20. https://doi.org/10.1007/s10071-018-1186-y

Knops, A., Thirion, B., Hubbard, E. M., Michel, V., & Dehaene, S. (2009). Recruitment of an area involved in eye movements during mental arithmetic. *Science, 324*, 1583–1585. http://dx.doi.org/10.1126/science.1171599

Knops, A., Viarouge, A., & Dehaene, S. (2009). Dynamic representations underlying symbolic and nonsymbolic calculation: Evidence from the operational momentum effect. *Attention, Perception & Psychophysics, 71*, 803–821. http://dx.doi.org/10.3758/APP.71.4.803

Liu, D., Cai, D., Verguts, T., & Chen, Q. (2017). The time course of spatial attention shifts in elementary arithmetic. *Scientific Reports, 7*(1), 921. doi:10.1038/s41598-017-01037-3

Liu, D., Verguts, T., Li, M., Ling, Z., & Chen, Q. (2017). Dissociated spatial-arithmetic associations in horizontal and vertical dimensions. *Frontiers in Psychology, 8,* 1741. https://doi.org/10.3389/fpsyg.2017.01741

Marghetis, T., Núñez, R., & Bergen, B. K. (2014). Doing arithmetic by hand: Hand movements during exact arithmetic reveal systematic, dynamic spatial processing. *The Quarterly Journal of Experimental Psychology, 67*, 1579–1596. http://dx.doi.org/10.1080/17470218.2014.897359

Masson, N., Letesson, C., & Pesenti, M. (2018). Time course of overt attentional shifts in mental arithmetic: Evidence from gaze metrics. *The Quarterly Journal of Experimental Psychology, 71*(4), 1009-1019. DOI: 10.1080/17470218.2017.1318931

Masson, N., & Pesenti, M. (2014). Attentional bias induced by solving simple and complex addition and subtraction problems. *The Quarterly Journal of Experimental Psychology, 67*, 1514–1526. http://dx.doi.org/10.1080/17470218.2014.903985

Masson, N., & Pesenti, M. (2016). Interference of lateralized distractors on arithmetic problem solving: A functional role for attention shifts in mental calculation. *Psychological Research, 80*, 640–651. http://dx.doi.org/10.1007/s00426-015-0668-7

Masson, N., Pesenti, M., Coyette, F., Andres, M., & Dormal, V. (2017). Shifts of spatial attention underlie numerical comparison and mental arithmetic: Evidence from a patient with right unilateral neglect. *Neuropsychology, 31*(7), 822-833. http://dx.doi.org/10.1037/neu0000361

Masson, N., Pesenti, M., & Dormal, V. (2017). Impact of optokinetic stimulation on mental arithmetic. *Psychological Research, 81*(4), 840-849. http://dx.doi.org/10.1007/s00426-016-0784-z

Mathieu, R., Gourjon, A., Couderc, A., Thevenot, C., & Prado, J. (2016). Running the number line: Rapid shifts of attention in single-digit arithmetic. *Cognition, 146*, 229–239. http://dx.doi.org/10.1016/j.cognition.2015.10.002

Mazhari, S., Shahrbabaki, M. E., Pourrahimi, A. M., Faezi, H., & Baneshi, M. R. (2019). The Effect of Spatial Numerical Association of Response Codes in Healthy Individuals and Schizophrenic Patients with Mixed-Reading Habit. *Iranian Journal of Psychiatry and Behavioral Sciences, 13*(1). doi: 10.5812/ijpbs.11717.

McCrink, K., Caldera, C., & Shaki, S. (2017). The early construction of spatial attention: Culture, space, and gesture in parent–child interactions. *Child Development.* https://doi.org/10.1111/cdev.12781

McCrink, K., & Opfer, J. E. (2014). Development of spatial-numerical associations. *Current Directions in Psychological Science, 23*(6), 439-445. https://doi.org/10.1177/0963721414549751

Nuerk, H. C., Patro, K., Cress, U., Schild, U., Friedrich, C. K., & Göbel, S. M. (2015). How space-number associations may be created in preliterate children: six distinct mechanisms. *Frontiers in Psychology, 6*, 215. https://doi.org/10.3389/fpsyg.2015.00215

Patro, K., & Haman, M. (2012). The spatial–numerical congruity effect in preschoolers. *Journal of Experimental Child Psychology, 111*(3), 534-542. https://doi.org/10.1016/j.jecp.2011.09.006

Patro, K., Nuerk, H. C., & Cress, U. (2016). Mental number line in the preliterate brain: The role of early directional experiences. *Child Development Perspectives, 10*(3), 172-177. https://doi.org/10.1111/cdep.12179

Peirce, J. W. (2007). PsychoPy—psychophysics software in Python. *Journal of Neuroscience Methods, 162*(1-2), 8-13. https://doi.org/10.1016/j.jneumeth.2006.11.017

Pérez, A. , García, L. , Valdés-Sosa, M. & Jaśkowski, P. (2011). Influence of the Learnt Direction of Reading on Temporal Order Judgments. *Psychology, 2*, 103-108. doi: 10.4236/psych.2011.22017.

Pinhas, M., & Fischer, M. (2008). Mental movements without magnitude? A study of spatial biases in symbolic arithmetic. *Cognition, 109*(3), 408-415. doi:10.1016/j.cognition.2008.09.003

Pinheiro-Chagas, P., Dotan, D., Piazza, M., & Dehaene, S. (2017). Finger tracking reveals the covert stages of mental arithmetic. *Open Mind, 1*(1), 30-41. https://doi.org/10.1162/OPMI_a_00003

Proctor, R. W., & Cho, Y. S. (2006). Polarity correspondence: A general principle for performance of speeded binary classification tasks. *Psychological Bulletin & Review, 132*(3), 416-442. http://dx.doi.org/10.1037/0033-2909.132.3.416

Rinaldi, L., Di Luca, S., Henik, A., & Girelli, L. (2014). Reading direction shifts visuospatial attention: An Interactive Account of attentional biases. *Acta Psychologica, 151*, 98-105. https://doi.org/10.1016/j.actpsy.2014.05.018

Rugani, R. (2018). Towards numerical cognition's origin: insights from day-old domestic chicks. *Proceedings of the Royal Society of London B: Biological Sciences*, 373(1740), 20160509. DOI: 10.1098/rstb.2016.0509

Rugani, R., & de Hevia, M. D. (2017). Number-space associations without language: Evidence from preverbal human infants and non-human animal species.

Psychonomic Bulletin & Review, 24(2), 352-369. https://doi.org/10.3758/s13423-016-1126-2

Rugani, R., Fontanari, L., Simoni, E., Regolin, L., & Vallortigara, G. (2009). Arithmetic in newborn chicks. *Proceedings of the Royal Society of London B: Biological Sciences, 276*(1666), 2451-2460. DOI: 10.1098/rspb.2009.0044

Rugani, R., Vallortigara, G., & Regolin, L. (2015). At the root of the left–right asymmetries in spatial–numerical processing: from domestic chicks to human subjects. *Journal of Cognitive Psychology, 27*(4), 388-399. DOI: 10.1080/20445911.2014.941846

Rugani, R., Vallortigara, G., Priftis, K., & Regolin, L. (2015). Number-space mapping in the newborn chick resembles humans' mental number line. *Science, 347*(6221), 534-536. DOI: 10.1126/science.aaa1379

Shaki, S., & Fischer, M. H. (2008). Reading space into numbers–a cross-linguistic comparison of the SNARC effect. *Cognition, 108*(2), 590-599. https://doi.org/10.1016/j.cognition.2008.04.001

Shaki, S., Fischer, M. H., & Petrusic, W. M. (2009). Reading habits for both words and numbers contribute to the SNARC effect. *Psychonomic Bulletin & Review, 16*(2), 328-331. DOI: 10.3758/PBR.16.2.328

Spalek, T. M., & Hammad, S. (2005). The left-to-right bias in inhibition of return is due to the direction of reading. *Psychological Science, 16*(1), 15-18. https://doi.org/10.1111/j.0956-7976.2005.00774.x

Starkey, P., & Cooper, R.G. (1980). Perception of numerosity by human infants. *Science, 210* (4473), 1033-1035. DOI: 10.1126/science.7434014

Stelmach, L. B., & Herdman, C. M. (1991). Directed attention and perception of temporal order. *Journal of Experimental Psychology: Human Perception and Performance, 17*, 539–550. http://dx.doi.org/10.1037/0096-1523.17.2.539

Toomarian, E. Y., & Hubbard, E. M. (2018). On the Genesis of Spatial-Numerical Associations: Evolutionary and Cultural Factors Co-Construct the Mental Number Line. *Neuroscience & Biobehavioral Reviews*, 90, 184-199. https://doi.org/10.1016/j.neubiorev.2018.04.010

Tversky, B., Kugelmass, S., & Winter, A. (1991). Cross-cultural and developmental trends in graphic productions. *Cognitive Psychology, 23*(4), 515–557. doi:10.1016/0010-0285(91)90005-9

Vallortigara, G. (2018). Comparative cognition of number and space: the case of geometry and of the mental number line. *Philosophical Transactions of the Royal Society B, 373*(1740), 20170120. DOI: 10.1098/rstb.2017.0120

van Dijck, J. P., & Doricchi, F. (2019). Multiple left-to-right spatial representations of number magnitudes? Evidence from left spatial neglect. *Experimental Brain Research, 237*(4), 1031-1043. https://doi.org/10.1007/s00221-019-05483-5

West, R.E., & Young, R.J. (2002). Do domestic dogs show any evidence of being able to count? *Animal Cognition, 5*, 183-186. https://doi.org/10.1007/s10071-002-0140-0

Wiemers, M., Bekkering, H., & Lindemann, O. (2014). Spatial interferences in mental arithmetic: Evidence from the motion–arithmetic compatibility effect. *The Quarterly Journal of Experimental Psychology, 67*(8), 1557-1570. doi:10.1080/17470218.2014.889180

Wynn, K. (1992). Addition and subtraction by human infants. *Nature, 358*, 749-750. https://doi.org/10.1038/358749a0

Zebian, S. (2005). Linkages between number concepts, spatial thinking, and directionality of writing: The SNARC effect and the reverse SNARC effect in English and Arabic monoliterates, biliterates, and illiterate Arabic speakers. *Journal of Cognition and Culture, 5*(1), 165-190. DOI: 10.1163/1568537054068660

Zohar-Shai, B., Tzelgov, J., Karni, A., & Rubinsten, O. (2017). It does exist! A left-to-right spatial–numerical association of response codes (SNARC) effect among native Hebrew speakers. *Journal of Experimental Psychology: Human Perception and Performance*, 43(4), 719. http://dx.doi.org/10.1037/xhp0000336

Table 1 - Predicted probability of "right first" responses as a function of operation and SOA

	SOA (msec)											
	-200	-100	-50	-33	-17	0	17	33	50	100	200	*Total*
Addition	.07	.22	.35	.40	.46	.51	.57	.62	.67	.80	.94	.51
Subtraction	.09	.22	.33	.37	.41	.46	.50	.55	.59	.72	.89	.47
Both	.08	.22	.34	.38	.43	.48	.53	.58	.63	.76	.91	.49

Table 2 - Predicted probability of "right first" responses as a function of language and operation

	SOA (msec)											
	-200	-100	-50	-33	-17	0	17	33	50	100	200	*Total*
French speakers												
Addition	.10	.25	.37	.41	.46	.50	.55	.59	.63	.75	.90	*.50*
Subtraction	.08	.20	.31	.35	.39	.44	.49	.53	.58	.71	.88	*.45*
Both	*.09*	*.23*	*.34*	*.38*	*.43*	*.47*	*.52*	*.56*	*.61*	*.73*	*.89*	*.48*
Arabic speakers												
Addition	.05	.19	.33	.39	.45	.52	.58	.64	.70	.84	.96	*.51*
Subtraction	.09	.24	.35	.39	.43	.48	.52	.57	.61	.73	.89	*.48*
Both	*.07*	*.21*	*.34*	*.39*	*.44*	*.50*	*.55*	*.61*	*.66*	*.78*	*.92*	*.50*

Note. Gray areas represent significant SOA differences between operations

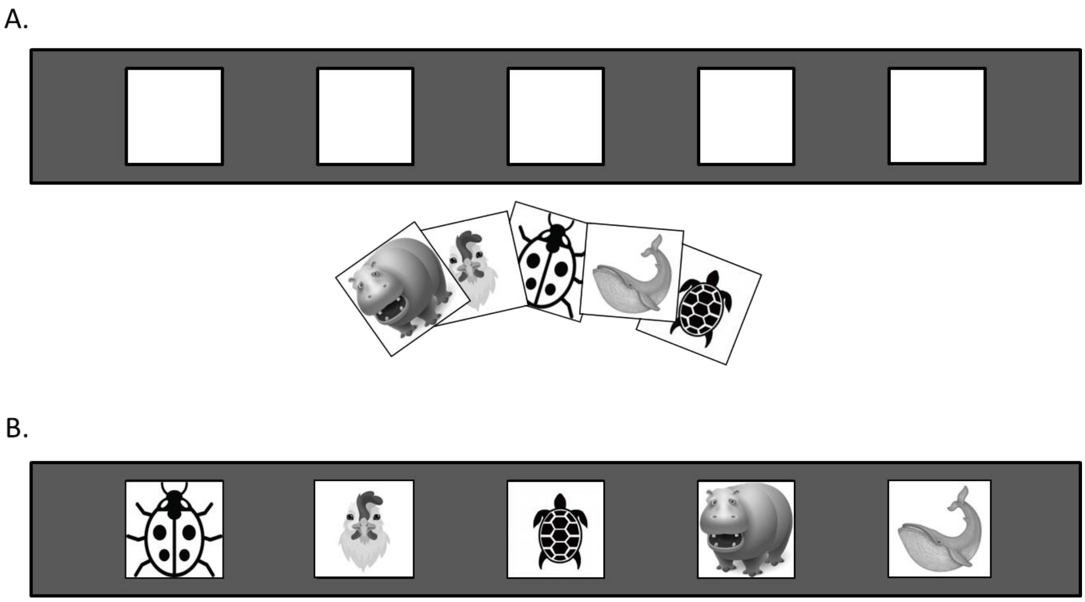

Figure 1: Schematic representation of the Ordering task. (A) Participants receive five cards of a series in a random order and have to identify what is represented on them (here: animals). (B) Participants order the series as a function of the instructed criterion (here: weight).

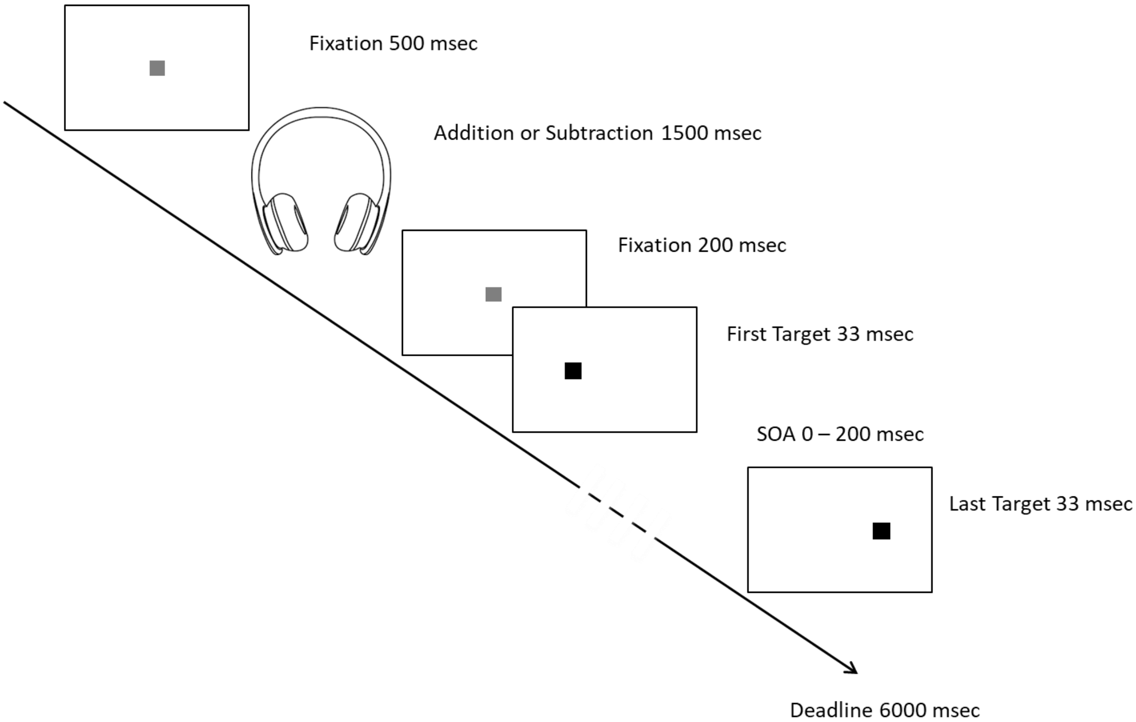

Figure 2: Sequence of events of one trial (here with a first target appearing on the left part of the screen).

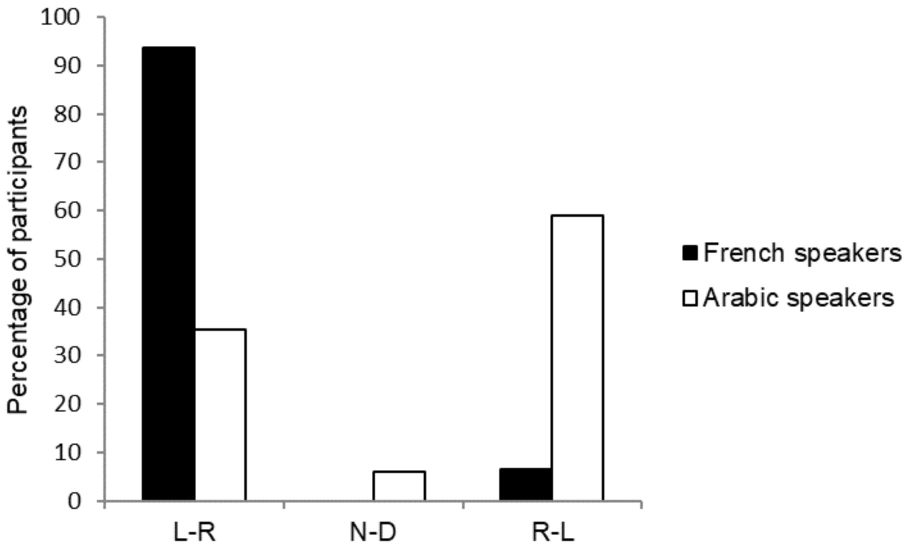

Figure 3: Percentage of participants classified as Left-to-Right (L-R), Non-Directional (N-D) or Right-to-Left (R-L) sorters as a function of Language (French *vs.* Arabic speakers).

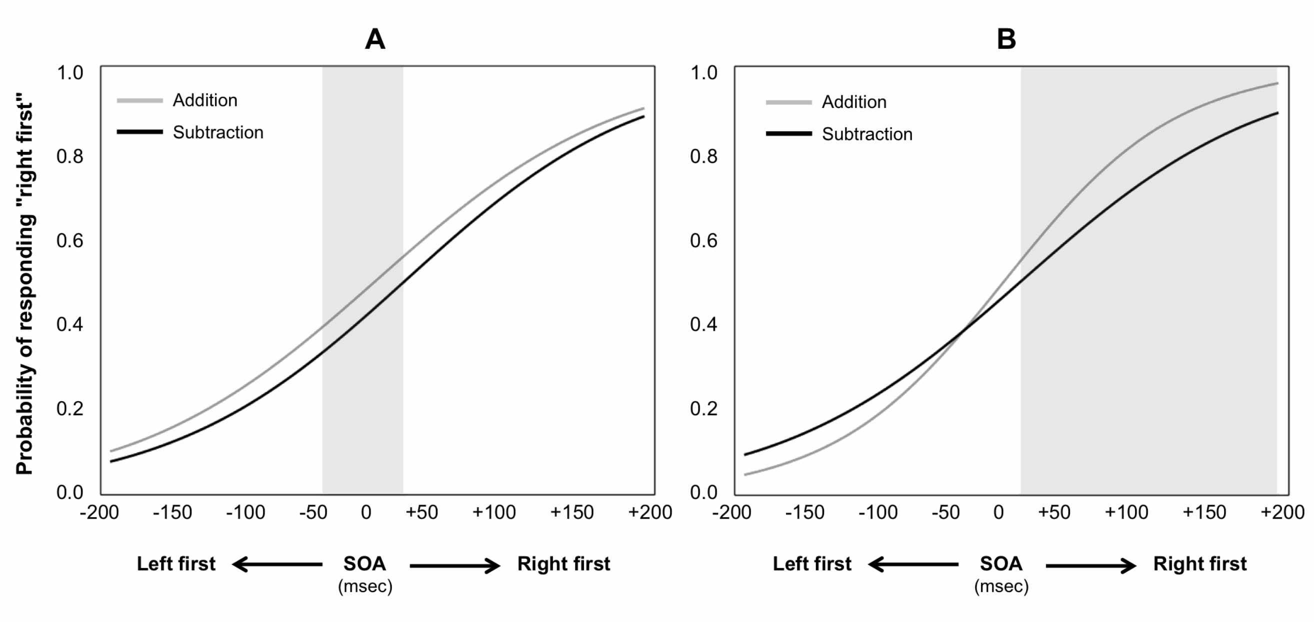

Figure 4. Predicted probability of "right first" response curves as a function operation in (A) French speakers and (B) Arabic speakers. Negative and positive SOA refer to left- and right-side stimulus precedence, respectively; gray areas show significant SOA differences between operations.

Appendix: Series and items of the ordering task

Series	Item 1	Item 2	Item 3	Item 4	Item 5
Dot Collection	2	5	8	12	20
Activity Duration	Going to the Toilet	Cooking Pasta	Watching Television	Sleeping	Building a house
Weight	Ladybird	Chicken	Tortoise	Hippopotamus	Whale
Price	Sandwich	Trousers	Smartphone	Diamond Ring	Luxury House
Football Team Strength	Egypt	United States	Italy	France	Belgium
Age	Baby	Child	Teenager	Adult	Oldman
Speed	Bicycle	Car	Racing Car	Airplane	Rocket
Bake a cake	Gathering the ingredients	Mixing the ingredients	Place cake in the oven	Set up on a plate	Eating the cake
Apple eaten	From plain apple to apple core				
Invention dates	Pottery	Catapult	Lightbulb	Airplane	Computer
Painting dates	Prehistoric	Ancient Egyptian	Medieval	18' century	Modern Art
Favourite sport	Tennis	Football	Swimming	Basketball	Cycling
Favourite dish	Spaghetti	Chocolate Cake	Bread and Jam	Tomato Soup	Hamburger
Favourite vacation location	Egypt (Gizeh Pyramids)	Italy (Rome)	USA (New-York)	England (London)	France (Paris)