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Brief article

Spatialization in working memory is related to literacy and reading direction: Culture "literarily" directs our thoughts

Alessandro Guida[a,*], Ahmed M. Megreya[b], Magali Lavielle-Guida[c,d], Yvonnick Noël[a], Fabien Mathy[e], Jean-Philippe van Dijck[f,g,1], Elger Abrahamse[f,h,i,1]

[a] *LP3C, Université Rennes, France*
[b] *Qatar University, Qatar*
[c] *Cabinet d'Orthophonie, St. Malo, UPMC, France*
[d] *Université Pierre-et-Marie-Curie (UPMC), Paris 6, France*
[e] *Université Côte d'Azur, France*
[f] *Department of Experimental Psychology, Ghent University, Ghent, Belgium*
[g] *Deparment of Applied Psychology, Thomas More, Antwerp, Belgium*
[h] *Basque Center on Cognition, Brain and Language, San Sebastian, Spain*
[i] *KERBASQUE, Basque Foundation for Science, Bilbao, Spain*

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ABSTRACT

The ability to maintain arbitrary sequences of items in the mind contributes to major cognitive faculties, such as language, reasoning, and episodic memory. Previous research suggests that serial order working memory is grounded in the brain's spatial attention system. In the present study, we show that the spatially defined mental organization of novel item sequences is related to literacy and varies as a function of reading/writing direction. Specifically, three groups (left-to-right Western readers, right-to-left Arabic readers, and Arabic-speaking illiterates) were asked to memorize random (and non-spatial) sequences of color patches and determine whether a subsequent probe was part of the memorized sequence (e.g., press left key) or not (e.g., press right key). The results showed that Western readers mentally organized the sequences from left to right, Arabic readers spontaneously used the opposite direction, and Arabic-speaking illiterates showed no systematic spatial organization. This finding suggests that cultural conventions shape one of the most "fluid" aspects of human cognition, namely, the spontaneous mental organization of novel non-spatial information.

1. Introduction

Human cognition is shaped by experience, with no small role for the socio-cultural context it is situated in (Pezzulo et al., 2012). Understanding the precise impact of cultural conventions on human cognition requires exploration at its most elementary levels. Here, we investigate how an important aspect of culture, the acquisition of reading/writing and its direction, influences serial order organization in working memory (WM), an elementary function that contributes to broad faculties such as language, reasoning, and episodic memory.

Previous work has shown how novel sequences of non-spatial items (e.g., letters, digits, words) are mentally organized from left to right in Western cultures. For example, van Dijck and Fias (2011) asked Flemish participants to maintain arbitrary sequences of fruit and vegetable words. Next, a binary choice reaction time task (e.g., left key press for fruits, right key press for vegetables) was performed on single fruit and vegetable words, but only when the word was part of the memorized sequence. Target words from later (as compared to earlier) positions in the WM sequence were increasingly responded to faster with right compared to left key presses. This result complemented previous work showing the same pattern but using overlearned sequences of items (abstract figures for Van Opstal, Fias, Peigneux, & Verguts, 2009; and words for Previtali, Hevia, & Girelli, 2010).

The "spatialization" of novel WM sequences has inspired the formulation of the mental whiteboard hypothesis: when confronted with an arbitrary sequence of items, the (Western) brain mentally organizes them from left to right within an internal space (the mental whiteboard) such that spatial attention controls later search and selection (Abrahamse, van Dijck, & Fias, 2017; Abrahamse, van Dijck, Majerus, & Fias, 2014). The interaction between serial order and spatial processing

* Corresponding author at: LP3C – Université Rennes, Place du Recteur Henri Le Moal CS 24 307, Bâtiment S – Bureau S 509, 35 043 Rennes Cedex, France.
E-mail addresses: alessandro.guida@univ-rennes2.fr, alessandro.guida.psychology@gmail.com (A. Guida).
[1] Shared senior authorship.

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for novel sequences has now been replicated across different tasks and stimuli (e.g., Antoine, Ranzini, Gebuis, van Dijck, & Gevers, 2017; Bottini, Mattioni, & Collignon, 2016; Ginsburg, Archambeau, van Dijck, Chetail, & Gevers, 2017; Guida, Leroux, Lavielle-Guida, & Noël, 2016; Rinaldi, Brugger, Bockisch, Bertolini, & Girelli, 2015; van Dijck, Abrahamse, Acar, Ketels, & Fias, 2014; van Dijck, Abrahamse, Majerus, & Fias, 2013). However, the origin of its left-to-right organization remains unknown.

The literature on spatial biases in information processing is large and generally features both biological and cultural determinants (for reviews, see McCrink & Opfer, 2014; Patro, Nuerk, & Cress, 2016; Rugani & de Hevia, 2017). Some results are difficult to explain in terms of cultural acquisition alone: non-human primates (Adachi, 2014; Drucker & Brannon, 2014) and even three-day-old chicks (Rugani, Vallortigara, Priftis, & Regolin, 2015) exhibit number-induced left-to-right spatial biases. As proposed by Rogers, Vallortigara, and Andrew (2013), it is possible that the left-to-right spatial bias across species is due to brain asymmetry and right hemisphere dominance, which can be linked to the asymmetry found in neglect patients, in which right neglect is less common (Beis et al., 2004), independently of culture (Bartolomeo, 2013).

Although biological factors play a role, culture seems to contribute as well. Reading/writing direction has been observed to influence external spatial attention across various operations, including line bisection (Rinaldi, Di Luca, Henik, & Girelli, 2014), inhibition of return (Spalek & Hammad, 2005), processing of facial expressions (Heath, Rouhana, & Ghanem, 2005), aesthetic preferences (Chokron & De Agostini, 2000), lateral motion perception (Maass, Pagani, & Berta, 2007), and the spatial organization of knowledge (Cooperrider, Marghetis, & Núñez, 2017; Fuhrman & Boroditsky, 2010), such as in the SNARC (Spatial Numerical Association Response Codes) effect[2] (Dehaene, Bossini, & Giraux, 1993; Shaki, Fischer, & Petrusic, 2009).

Beyond the nature vs. nurture dichotomy, accounts of spatial biases, such as the SNARC effect (e.g., Abrahamse, van Dijck, & Fias, 2016; De Hevia, Girelli, & Macchi Cassia, 2012; Nuerk et al., 2015), tend to integrate both, whereby spatial biases observed in human adults can be considered the product of interactive biological and cultural forces. For example, De Hevia et al. (2012) suggested that biological factors, such as the advantage of processing the left hemispace (De Hevia, Girelli, Addabbo, & Macchi Cassia, 2014) and increasing order (De Hevia et al., 2017) are later in the development, modulated and influenced by cultural conventions such as reading/writing direction. Importantly, the influence of cultural conventions seems to arise before formal reading/writing acquisition; four-year-old children already exhibit culture-specific spatial biases (McCrink, Shaki, & Berkowitz, 2014; Opfer, Thompson, & Furlong, 2010). This spatial influence is thought to occur mainly by means of observational learning (for a review, see McCrink & Opfer, 2014; Patro et al., 2016), for instance through the interaction between infants and caregivers (McCrink, Caldera, & Shaki, 2017).

Currently, it is not known whether the spontaneous spatialization of serial order in WM is influenced culturally. Hence, the first aim of the present study was to test whether the direction of spatialization in WM is dependent on reading/writing direction. The second aim was to test whether formal reading/writing acquisition is crucial for spatialization. Guida and Lavielle-Guida (2014) proposed that spatialization could be likened to retrieval mechanisms used by expert mnemonists (e.g., Guida, Gobet, Tardieu, & Nicolas, 2012), who memorize a virtual spatial context (e.g., method of loci) to subsequently retrieve the memoranda. Although the left-to-right spatialization used by all-comers is much simpler compared to the method of loci, the same underpinning processes due to practice could be at play. In the case of all-comers, it would depend on reading/writing expertise acquired through formal training in school.

In the present study, we tested three groups of participants, left-to-right Western readers, (monolingual) right-to-left Arabic readers, and (monolingual) Arabic-speaking illiterates, who were required to memorize random (and non-spatial) sequences of color patches presented in the middle of a screen. Participants had to determine whether a subsequent probe (another color patch) was part of the memorized sequence (e.g., press left key) or not (e.g., press right key). If reading/writing direction drives the direction of spatialization, then this spatial bias should vary according to the reading/writing system, and if formal reading/writing acquisition is necessary, spatialization should be absent in the illiterate group.

2. Method

2.1. Participants

Forty Egyptians participated in this experiment: 20 Arabic literates (strictly monolingual; all right handed, 12 females, age: M = 38.95, SD = 3.02) and 20 Arabic illiterates (strictly monolingual; all right handed, 5 females, age: M = 34.7, SD = 4.43). For the latter group, illiteracy was related either to their parents lack of interest in sending them to school ($n = 7$) or to economic reasons ($n = 13$). Finally, 20 Western literates also participated in the current study; 10 were Belgian Dutch speakers and 10 were French speakers (all right handed, 13 females, age: M = 38.25, SD = 4.04). We calculated a priori sample size on the basis of the data of one of our previous experiments that most closely matched the current experimental design. A power analysis of Experiment 4 from Ginsburg et al. (2017) resulted in a required sample size of 19 given a power of 0.9. Hence, we recruited 20 participants per group.

2.2. Material

The dataset can be uploaded together with the manuscript (see Supplementary Material). Participants were given two blocks, each consisting of 16 WM sequences of four different-colored patches. The sequences were created by pseudo-randomly sampling without replacement from a pool of eight colors (black, orange, blue, green, white, red, pink, and yellow). For each participant, every color appeared 16 times in total and four times at each sequential position. Concerning the probes, there was an equal number of positive ("yes") and negative ("no") probe trials. In total, for each participant, 512 probes were used (each color was used 64 times). Each sequential position was equally probed by each color.

2.3. Procedure

Participants were tested individually on a computer in the presence of an experimenter. During a familiarization phase, participants were shown the eight colors of the experiment and were asked to name them in order to ascertain that they could correctly identify them. In the test phase, all trials began with a 500 ms blank screen followed by a "+" sign presented in the middle of the screen for 500 ms, indicating that a to-be-memorized sequence was going to appear. Immediately after, four colored patches were sequentially displayed in the middle of the screen at a rate of 5000 ms per item. A blank screen then immediately appeared for 1000 ms, followed by a "+" sign for 500 ms in the middle of the screen, indicating that a probe was going to appear. When the probe was displayed, participants answered with a left or right key press. For each WM sequence, 16 probes appeared, after which participants were asked to recall the whole sequence and the experimenter pressed a button to pass onto the next trial.

In each of the two blocks, the mapping of "yes" and "no" responses onto the left and right CTRL buttons was specified. Half of the

[2] In the SNARC effect, smaller numbers are associated preferentially with left-hand responses and larger numbers with right-hand responses. The pattern is reversed in right-to-left reading/writing countries.

participants started the experiment (first 16 trials) with the right CTRL key assigned to “yes” and the left CTRL assigned to “no” and ended the experiment (last 16 trials) with the right CTRL assigned to “no” and the left CTRL assigned to “yes”. For the other half of the participants, these mappings were reversed. The experiment lasted 45 min. The Egyptian participants used Colloquial Arabic to name the colors.

3. Results

Analyses were conducted on the correctly responded trials, which contained a probe that belonged to the memorized sequence (i.e., “yes” responses). Trials with reaction times (RT) that fell outside the range of mean RT plus/minus two and a half SD (i.e., outliers) were excluded (3.2%). Data of one participant (literate Arabic group) were removed from analyses due to overall chance level performance (51% correct). Accuracy for the Western literates, Arabic literates, and Arabic illiterates was 95%, (SD = 0.03), 93% (SD = 0.05), and 91% (SD = 0.06),[3] respectively. The correlation between RT and accuracy revealed that there was no indication of a speed-accuracy trade-off in any of the three groups, $r = 0.02$, $p = .97$, $r = -0.62$, $p = .10$, $r = -0.82$, $p = .01$, respectively.

As RT distribution was skewed, mean RTs within each design cell for each participant were log-transformed to normalize the distribution. A 3 × 4 × 2 ANOVA (see Table 1 for the results) was conducted with a between-subjects factor *Literacy* (3; Western literates, Arabic literates, Arabic illiterates) and two within-subjects factors, *Position in the Sequence* (4; sequence positions 1 to 4) and *Hand of Response* (2; left hand versus right hand).

Concerning the main effects, *Position in the Sequence* was significant. For positions 1–4, the estimated mean RTs were 779 (SD = 156 ms), 785 ms (SD = 171 ms), 811 ms (SD = 178 ms), and 814 ms (SD = 171 ms). This increase was linear, $F(1, 56) = 16.88$, $p = .0001$ (no quadratic relation: $F(1, 56) = 0.03$, $p = .87$). However, when *Position in the Sequence* was analyzed for each group, the increase was linear only for the Arabic literates, $F(1, 56) = 14.10$, $p = .0004$, whereas it was quadratic for the Western literates and the Arabic illiterates, $F(1, 56) = 5.43$, $p = .02$, $F(1, 56) = 3.84$, $p = .05$, respectively[4].

Two interactions were significant. First, *Hand of Response* varied as a function of *Literacy,* but more importantly for our purpose, the interaction between *Position in the Sequence* and *Hand of Response* varied as a function of *Literacy* (Fig. 1). To obtain further insight, we tested the interaction between *Position in the Sequence* and *Hand of Response* for each group.

For the Western literates, a significant interaction between *Position in the Sequence* and *Hand of Response* was observed, $F(3, 168) = 4.67$, $p = .004$. A polynomial contrast of *Position in the Sequence* in its interaction with *Hand of Response* revealed a linear relationship, $F(1, 56) = 6.08$, $p = .02$, but not a quadratic relationship, $F(1, 56) = 0.24$, $p = .63$ (for a similar approach, see van Dijck et al., 2013, 2014).

For the Arabic literates, the same analysis resulted in a significant interaction between *Position in the Sequence* and *Hand of Response*, $F(3, 168) = 2.89$, $p = .04$, and the polynomial contrast of *Position in the Sequence* in its interaction with *Hand of Response* was significantly linear, $F(1, 56) = 5.59$, $p = .02$, but not quadratic, $F(1, 56) = 1.19$, $p = .28$. Fig. 1 shows that the RT advantage for the right compared to the left hand decreases as one advances through the positions, whereas the inverse pattern is found for Westerners.

Concerning the Arabic illiterates, no interaction between *Position in the Sequence* and *Hand of Response* was observed, $F(3, 168) = 0.17$, $p = .91$, suggesting that positional information in WM was not systematically associated with space. The polynomial contrast (for *Position in the Sequence*) of the interaction also failed to reach significance for a linear and a quadratic relationship, with $F(1, 56) = 0.11$, $p = .74$, and $F(1, 56) = 0.12$, $p = .73$, respectively. To directly test the null hypothesis concerning the interaction for this group, a Bayesian factor (BF) analysis (Jeffreys, 1961) was performed using the BIC (Bayesian Information Criterion; Schwarz, 1978) for the interaction model (H_1) and the null model (H_0), 62,312 versus 62,290, respectively. Then, the BF_{10} was computed using the following formula:

$$BF_{10} = e^{\left(\frac{\Delta BIC10}{2}\right)}.$$

As described by Wagenmakers (2007), with equal priors on the models, this amounts to a posterior probability of H_0 of more than 0.9999 ($Pr_{BIC}(H_0|D) = 59{,}874/59{,}875$), which represents very strong evidence for H_0 or very strong evidence against the interaction, according to Raftery (1995).

Table 1
Summary of ANOVA Results for “Position in the Sequence”, “Hand of Response”, and “Literacy”.

Effect	F	p	Partial η²
Hand	0.23	0.63	0.004
Position	6.02	0.0006	0.10
Literacy	2.80	0.07	0.09
Literacy × Position	1.80	0.10	0.06
Position × Hand	0.63	0.59	0.01
Literacy × Hand	6.09	0.004	0.18
Position × Hand × Literacy	3.53	0.003	0.11

4. Discussion

The present study shows for the first time that the spontaneous, spatial organization of novel item sequences in the mind varies as a function of reading/writing direction and is related to literacy: a left-to-right organization was observed for Western readers, a right-to-left organization was observed for Arabic readers, and no reliable spatial bias was observed for Arabic-speaking illiterates.

A first implication of these results is that spatialization in WM is in line with the spatial biases presented in the introduction (e.g., the SNARC), its direction is culture dependent. Even if spatial biases begin ontogenetically (e.g., chicks in Rugani et al., 2015) and phylogenetically (e.g., seven-month-old infants in Bulf, de Hevia, Gariboldi, & Macchi Cassia, 2017), as culture-free processes, culture does intervene at some point (e.g., McCrink et al., 2014). We now know that this is also the case for spatialization. Therefore, although the spatial biases found in chicks and babies may be precursors (De Hevia et al., 2012; Rugani & de Hevia, 2017) of spatialization in WM, for humans, the direction of the initial left-to-right bias can be overcome and reversed via culture-dependent acquisition.

Second, our results point to the pre-requirement of formal reading/writing training for spatialization in WM to be observed in the first place. Hence, even if one considers the spatial biases found in chicks and babies as precursors, these initial biases seem to necessitate a kind of consolidation through training before they can be translated into spatialization. This aligns with the critical role of expertise/practice (Guida & Lavielle-Guida, 2014).

However, these results are not in accordance with recent findings

[3] The difference between the accuracy scores was globally significant, $F(2, 56) = 4.94$, $p = .01$, but when tested two by two, only the Western literates and Arabic illiterates differed significantly, $t(38) = 3.29$, $p = .002$.

[4] Both quadratic (e.g., Bottini et al., 2016; Guida et al., 2016) and linear (e.g., van Dijck & Fias, 2011; van Dijck et al., 2013) trends are found in the spatialization literature. Based on Sternberg's work (e.g., Sternberg, 1975, 2016), linear trends are often attributed to serial scanning strategies (van Dijck & Fias, 2011; van Dijck et al., 2013). Quadratic trends are often observed in memory research (at least since Ebbinghaus, 1902; for RTs specifically, see McElree & Dosher, 1989, 1993; Monsell, 1978), however, within the spatialization literature, no specific interpretation has been attributed to quadratic trends, which could be linked to more direct and parallel access (McElree & Dosher, 1989, 1993). It is to be noted that the distinction between serial scanning and parallel access is controversial and highly debated (e.g., McElree, 2006; Sternberg, 2016).

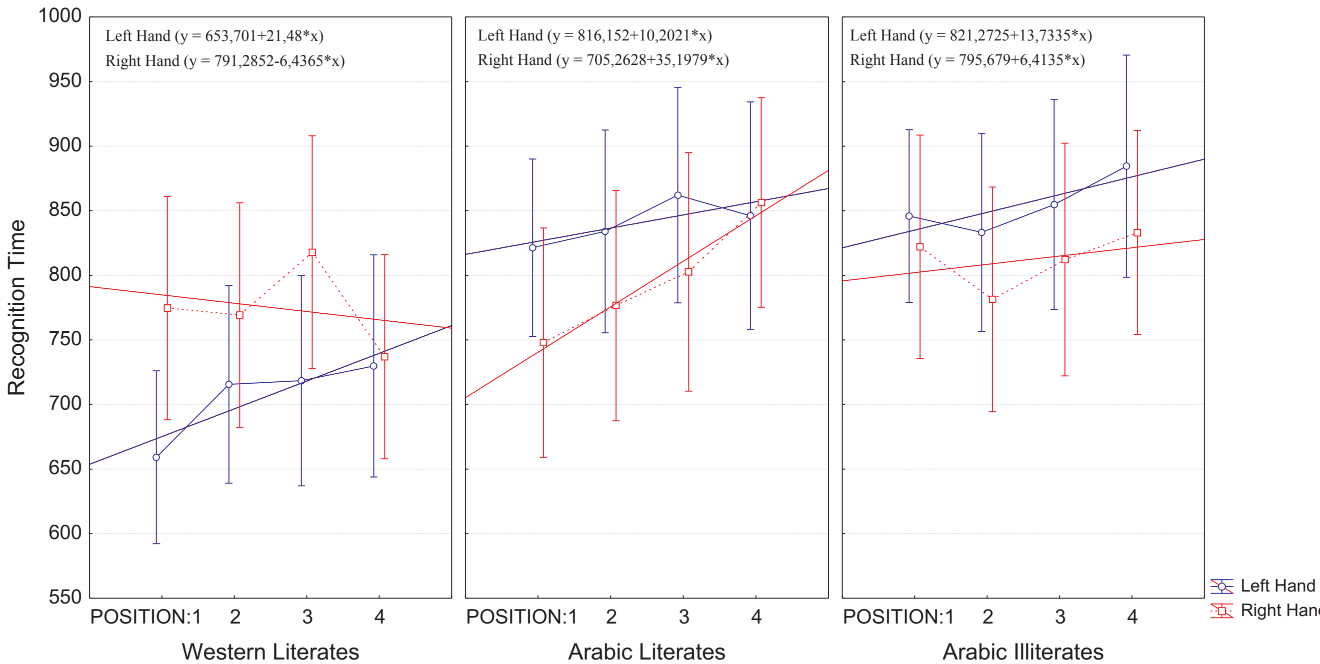

Fig. 1. Mean and linear fitted reaction times as a function of probed position in the sequence, hand of response and literacy. Error bars are confidence intervals.

showing that culturally related spatial biases in number processing arise before formal reading/writing acquisition (for reviews, see McCrink & Opfer, 2014; Patro et al., 2016). This discrepancy may point to a qualitative difference between number- and WM-induced spatial biases. However, it could also be due to the specificity of illiterates. Indeed, previous results have shown an absence of spatial biases in illiterates (Shaki, Fischer, & Göbel, 2012; Zebian, 2005), but we now know that spatial biases (e.g., Opfer et al., 2010) can be found in four-year-old children with no formal reading/writing acquisition. This discrepancy could be due to illiterates lacking early enculturation. Further work is needed to test spatialization in four-year-old children from left-to-right and right-to-left reading/writing countries to reach a more definitive conclusion.

Lastly, our results suggest that the elements we keep in mind and think about—our thoughts—naturally assume the direction that dominates our language system. As such, culture seems to "literarily" direct our thoughts. This idea fits well with the observed impact of reading direction on forward scanning in WM (Kessler & Oberauer, 2015). It can also explain recent results (McCrink & Shaki, 2016) showing that our capacity to learn novel material can be increased if material is presented congruently to one's language reading-writing direction and thus to one's direction of thought.

Overall, in the present study, we showed that our minds organize non-spatial information in WM in a *culturally determined* way. This novel insight reveals the fascinating depth of the impact of cultural conventions on human cognition and may ultimately support new development in training and pedagogy.

Authors contribution

AG developed the study concept. EA, AG, MLG, FM, AM, YN, JPVD (by alphabetical order) contributed to the study design, analysis or interpretation of data. Testing and data collection were performed by AM (Arabic participants), JPVD (Western participants) and AG (Western participants). AG and JPVD (by alphabetical order) performed the data analyses. EA, AG, and JPVD (by alphabetical order) contributed to the theoretical framework. EA and AG (by alphabetical order) drafted the final manuscript, and EA, AG, MLG, FM, AM, YN, JPVD (by alphabetical order) provided critical revisions and approved it.

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Conflict of interest statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2018.02.013.

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