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SPATIALIZATION IN WORKING MEMORY AND ITS RELATION TO MATH ANXIETY

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ABSTRACT

Working memory (WM) is one of the most important cognitive functions that may play a role in the relation between math anxiety (MA) and math performance. The processing efficiency theory proposes that the rumination and worrisome thoughts (induced by MA) result in less available WM resources (which are needed to solve math problems). At the same time, high MA individuals have lower verbal and spatial WM capacity in general. Extending these findings, we found that MA is also linked to the spatial coding of serial order in verbal WM: Subjects who organize sequences from left-to-right in verbal WM show lower levels of MA compared to those who do not spatialize. Furthermore, these spatial coders have higher verbal WM capacity, better numerical order judgement abilities and higher math scores. These findings suggest that that spatially structuring the verbal mind is a promising cognitive correlate of the MA and opens new avenues for exploring causal links between elementary cognitive processes and the MA.

Keywords: OPE, math anxiety, working memory, order processing

INTRODUCTION

Math anxiety (MA) is the experience of apprehension that arises in some individuals when dealing with mathematics [1]. MA can have a detrimental impact on mathematical performance [e.g., 2,3]. Although related, MA cannot be reduced to either test or general anxiety [4]. At this moment, the exact prevalence of MA is unknown as estimates range from 10 to as many as 30% of the population [5,6]. Considering the significance of mathematics, it is important to obtain a better insight in the factors that underly the negative relation between MA and mathematical performance.

Considerable effort has been made to understand why mathematical performance is impacted by MA. Besides other cognitive factors (see below), working memory (WM) is considered as one of the key cognitive functions. WM is a limited capacity system allowing to flexibly, but temporarily, store a restricted number of items [7]. An influential theory assigning a major role to WM is the processing efficiency theory [8]. This theory suggests that MA causes interference in WM, due to worrisome thoughts, which occupy the WM resources needed to solve the math problems. Support for this idea came from studies where high and low MA subjects completed math problems that differed in WM load. Where no group differences were found for easy problems, the low MA group outperformed the high MA group for the problems that required (more) WM [2,3].

Follow-up studies found that MA not only relates to WM while performing mathematics. When tested outside a math context, significant differences in verbal and/ or visuo-spatial WM capacity were also found between high and low MA individuals [e.g., 9–11]. This indicates that the link between MA and WM can also be caused by factors beyond the immediate and momentaneous negative effects of anxiety. At this moment, however, it is still debated whether the presence of such deficits creates a vulnerability to develop MA, that avoidance behavior induced by (early) MA has resulted in less training occasions for these functions to develop, or whether the two amplify each other through development (for a discussion see [12]).

So far, studies investigating the link between WM and MA mainly focused on capacity [3,9,11]. Yet, individuals do not only differ in the number of items they can store, but also in the way they keep track of the serial order in which the items are presented [13]. Recently, it has been found that high MA individuals are less efficient in judging the order of numerical triplets compared to low MA individuals[14]. Although this ability draws upon the long-term memory (LTM) knowledge of (numerical) order, cognitive and neural evidence suggest that serial order coding in LTM and WM draw upon the same coding mechanisms [e.g.,

[15]. More precisely, a dedicated role for the spatial coding of serial order in both LTM and WM has recently been proposed [16]. Indeed, next to a spatial representation of serial order in LTM [e.g., 17,18], it has been found that information serially ordered in verbal WM is mentally coded in space according to our reading habits. In left-to-right reading cultures, verbal sequences are horizontally organized in WM, with begin items being associated with left, and end items with right. This observation is called the Ordinal Position Effect (OPE) and has been replicated across various experimental settings [e.g., 19–25]. Currently however, it is unknown whether MA is associated with differences in the spatialization of serial order in WM.

At first sight, it seems obvious that organizing WM in a systematic spatial fashion is beneficial for WM efficiency and for tasks depending on it [26]. The first aim of this study was to determine whether spatialization can be an explanatory factor for MA. More precisely, we hypothesize that spatially organizing verbal sequences in mind would make WM more efficient and should therefore be associated with lower levels of MA. Next, to provide further support for the idea that spatialization is indeed associated with increased WM efficiency, we directly investigated the interconnections between spatialization, (verbal and spatial) WM capacity and numerical order processing. Finally, because MA, WM and order processing are also related to mathematics performance [27,28], we verified whether the benefits of spatialization also generalizes to this related domain.

Instead of correlational analyses, we used a novel approach to determine the impact of spatialization: We identified those subjects who show a reliable OPE and compared their MA and task performance to those who do not show the effect [29–31]. This choice was motivated with two arguments. (1) Tasks, like those used to measure the OPE, typically suffer from lower reliability[30,32], with is detrimental for correlational analyses. Second, because the OPE is a reflection of average reaction time differences (see results), the size of the OPE not necessarily relates to the systematicity of the effect (because the size can be influenced by a few slow or fast trials). This makes the (the lack of) results difficult to interpret. By comparing the individuals who systematically show the OPE to those who do not, we obtain results which are more robust and easier to interpret.

METHODS

Participants

137 subjects (on average 20.520 years (SD=4.080); 91 females; 46 males) participated in this study. Only 3 subjects were familiar (able to understand, read and/ or write) with language with a right-to-left reading direction, all other subjects were only familiar with left-to-right oriented languages. They were all first-year bachelor students in applied psychology and were tested in groups of 30 subjects at Thomas More University of Applied Sciences. A test-session lasted about two hours. They participated to obtain course credits and signed an informed consent beforehand. The research complied with the guidelines of the Independent Ethics Committee of the Department of Psychology and Educational Sciences of Ghent University.

Procedure

All tasks were computerized using E-Prime 2. All responses were collected using the keyboard. The tasks reported here made part of two different test batteries. The first battery consisted of the Ordinal Position task (OPT), a numerical order judgment task, the Corsi-block task, the backward digit span task, a math task, and the Abbreviated Math Anxiety Scale (AMAS). Ninety-six subjects completed these tests in this order. The second battery started with[1] a processing- speed task (i.e., color classification), followed by parity judgement, the OPT, a math task, the AMAS and ended with a processing-speed task. This battery was administered to 41 subjects. The second battery was part of a replication study that was conducted for other purposes. For this reason, the processing speed tasks, and parity judgment will not be discussed here. Below a description will be given of the tasks used in this study.

[1] Although the order of the tasks differed between both batteries, the math tasks and the AMAS were always presented at the end of the test session. This makes it unlikely that the results of the OPT were "contaminated" by the MA that could have been induced by the math tasks.

Materials

Abbreviated Math Anxiety Scale (AMAS)

Math anxiety was assessed using the Abbreviated Math Anxiety Scale [33]. The original AMAS-items were translated into Dutch. Participants were asked to indicate on a 5-point Likert scale (1=low anxiety, 5=high anxiety) how anxious they would feel in each of the nine described math situations. The average score on these nine items was calculated as an index, with higher values corresponding to higher anxiety. The AMAS is characterized by adequate reliability and validity in the original English version as well as in several other languages [33–35]. The original English version had an internal consistency of α=.90 and a test-retest reliability of r_{tt} = .85 [33]. Reliability of the current translation of the AMAS used in both batteries reported here can be considered as very good (Battery 1: Cronbach's alpha: .88; Battery 2: Cronbach's alpha: .85).

Ordinal Position Task (OPT)

To measure the Ordinal Position Effect (OPE), we used a variant of the fruit-vegetable categorization task of van Dijk & Fias [36]. In this task, each block started (Phase 1) with the successive presentation of four words referring to fruits or vegetables randomly chosen from the following closed set: appel (Dutch for apple), peer (pear), kiwi (kiwi fruit), druif (grape), sla (lettuce), erwt (pea), radijs (radish), ajuin (onion). Each word (ca. 35 x 5 mm) was presented in the center of the screen for 1500ms with an inter-item-interval of 500ms. Subjects were instructed to memorize all words in the order of presentation. Following the final word, a 2000ms period elapsed, allowing rehearsal, after which the fruit-vegetable categorization task started (Phase 2). During this part, all words from the closed set were randomly presented twice with the restriction that the same word could not be repeated on consecutive trials. To ensure WM access, subjects were instructed to respond only to the memoranda and to refrain from responding (no-go trials) when the word did not belong to the memorized sequence. A trial consisted of a fixation point (500 ms) followed by a target. Subjects were instructed to press the left key (the letter "f") for vegetables and the right key (the letter "j") for fruits. Halfway the experiment, this response mapping was reversed. The response deadline was set to 1500ms. After this period or after a response, the screen went black and following an inter-trial interval of 1000ms after which the next trial was initiated. Finally (Phase 3), sequence maintenance was verified by three subsequent statements on serial order (e.g., “Kwam appel voor sla?”, Dutch for “Was apple preceded by lettuce?”). These statements were composed of the 3 possible pairs of subsequent WM items of which the order either corresponded or not to the order of the WM sequence (items were vertically arranged to avoid any horizontal association and all statements had the same structure: was X preceded by Y). Speed and accuracy were stressed during fruit-vegetable categorization (Phase 2), accuracy during the memory verification task (Phase 3). For each response mapping, one practice sequence preceded the experimental blocks. The participants of the first battery completed in total 16 experimental blocks (8 blocks per response mapping) while the subjects of the second battery completed experimental 24 blocks (12 blocks per response mapping). Given the 4 (WM-position) by 2 (response side) factorial structure of the task, this resulted in 16 and 24 trials per condition. Memory sequences and probes presented during the retention interval were constructed such that over the entire experiment, each word appeared an equal number of times on each position in the memory sequence and as a go/no-go trial. For this task, the average reaction time of the correctly classified go-no trials of the correctly judged sequences in phase 3 were used to calculate the OPE (see below for the exact calculation of this effect).

Numerical order judgement task

To measure the ability to judge the order of numerical triplets, we used the order judgment task of Lyons & Beilock [27]. In this task participants determined whether triads of Arabic digits were all in increasing order or were unordered (irrespective of the numerical distance between them; for the stimulus set see [27]) by pressing the letter “f” (for unordered) or “j” (for increasing) on the keyboard. A trial started with the presentation of the triplet for 1500ms, followed by an empty screen. Both events were interrupted when a response was given, after which the ITI was initiated (1500ms). The task consisted of two blocks of 92 trials with a 30-second break in between. In half of the trials, the triplets were (not) ascending. The test started with a four practice trials with feedback. For this task, the average reaction time of the correct trials was considered as the index for order judgement ability.

Corsi-blocks task

To measure visuo-spatial WM capacity, a computerized 2D-version of the Corsi-block task was administered. Nine grey squares (35x35mm) presented on a white background, were positioned according to Corsi’s [37] original configuration. On this configuration, sequences of locations were indicated, and the task was to remember and recall these sequences in the order of presentation. Sequences were presented with an increasing number of items (three to nine items: three sequences per length). When all three sequences of a particular length were incorrect, the task was ended. The individual capacity was defined as the total amount of sequences correctly recalled during data-collection (maximum score of 21). A trial started with the presentation of the configuration (1200ms) followed by the successive presentation of the target positions by a color change of those squares (1000ms each with 500ms in between). On completion of the sequence, the configuration reappeared after an empty screen (2000ms) and participants were required to reproduce the memorized sequence by clicking on the squares with the computer mouse. A produced sequence was considered correct when all relevant squares were indicated in the order of presentation. Feedback appeared at the end of each sequence (number of items on the correct location). The test started with a 3-item practice sequence.

Backward Digit Span

To measure verbal WM capacity, we used a computerized version of the backward digit span task from the WAIS-IV [38]. For this purpose, sequences of digits had to be memorized and recalled in reversed serial correct order. Sequences were presented with an increasing number of items (three to nine items: three sequences per length). When all three sequences of a particular length were incorrect, data-collection was ended. The individual WM capacity was defined as the total amount of sequences correctly recalled during data-collection (maximum score of 21). A trial started with an empty screen (1500ms) followed by the digit (1250ms) which were separated by a blank screen (750ms). During retention, the screen remained empty (1500ms) until the request for recall. Participants typed their responses and the digits entered were displayed at the bottom of the screen. A trial was correct when the digits from the memorized sequence were reproduced in the reserved order of presentation. Feedback appeared at the end of each trial (correct or wrong). To get accustomed with the test, participants started with a 3-item practice sequence.

Math task

For the math task, we combined (parts of) two existing production tests: a speeded mental arithmetic task [39] and a curriculum-based math test for the last year of primary school [40]. The speeded arithmetic task was administered first in the following order: addition, subtraction, multiplication, division. Each block ended after a completion of 50 items or after the response deadline of 2 minutes. The curriculum-based part consisted of 4 blocks administered in the following order: word problems, algebra, fractions, geometry. Each block ended after a completion of 10 items or after the response deadline of 3 minutes. In both tests, all problems were presented in the center of the computer screen and responses were collected via the keyboard. A pause of 30 seconds divided the different blocks. For each task (arithmetic or curriculum based) the percentage of correct trials was calculated. The overall math score was obtained by averaging these percentages.

Data-preparation and subject selection

To allow maximal individual differences, the data of the AMAS, the backward digit span, the Corsi-block task and the math task were considered without trimming (except in cases the subject did not follow the instructions). For both the OPT and the numerical order judgement task, data-trimming was applied at the trial level. After this trimming, the data of all subjects who performed above chance level were considered. For the OPT, the analyses were conducted on the average reaction times (RT's) of correct responses only. This were the correctly categorized go-trials trails from Phase 2 (see above) of WM sequences which were correctly maintained till the end of the block (i.e., correctly judged in Phase 3). For the numerical order task, this were the correctly judged trials. To remove outlying RTs in the OPT, an average +/- 2.5 SD trimming was applied to each task condition of each participant separately (as such, on average < 1% the data were trimmed for the OPT). Furthermore, only the data of participants who correctly followed the go/ no-go instructions (i.e., responding to go-trials but not to no-go-trials, irrespective whether the categorization was correct) above chance level (i.e., 143 of the 256 trials correct for Battery 1 and 211 of the 384 trials correct for Battery 2; both Chi-square (3.73) $p<.05$), were included in the dataset. This resulted in an exclusion of 16 participants. Finally, the calculation of the OPE slopes can only be performed on datasets without empty cells in the WM-position by response side design. As such, no OPE was estimated for another 7 participants (this were merely subjects who performed at random in Phase 3). In total, the OPE was determined for 114 participants. For the numerical order task, average RT +/- 2.5SD trimming was applied to all correct trials, irrespective of the condition (ascending or unordered). This resulted in a trimming of 2% of the data. Data is available at https://osf.io/vadh6/.

Data- analyses

The analyses were organized in three parts. (1) To see whether we could replicate the link between MA, working memory, numerical order judgement and math skill, we performed Pearson or Spearman correlations, depending on whether deviations from bivariate normality were detected (i.e., when the p-value of the associated bi-variate Shapiro-Wilks test was significant). (2) Next, we investigated whether spatial coding of serial order in verbal WM relates to MA. We first determined which individuals showed a reliable OPE to compare this group with those who do not show a reliable OPE. To determine the OPE, the average RTs for left- and right-hand responses were calculated for each WM position separately. Next, for each WM position, the RT of the left-sided responses were subtracted from the RTs of the right-sided responses to obtain difference scores. These scores were entered in a regression analysis with WM position as predictor. With this approach, a negative unstandardized regression weight reflects (relatively) faster left-sided responses for begin items of the memorized sequence, and (relatively) faster right-sided responses for end items (and thus a left-to-right mapping of serial order to space). The slope is expressed in milliseconds and its value corresponds to the change in relative advantage of right-sided responses in comparison to left-sided responses when the ordinal position of the object increases by one. To determine the presence of a reliable OPE at the individual level, we used the bootstrapping technique that was recently developed by Cipora and colleagues (ref. [30]; for the R-scripts see: https://osf.io/n7szg/). The logic behind this technique is the following: For each participant within each experimental cell (WM position by response side) we sampled with replacement the number of trials that was present in the original experiment (16 or 24 trials per experimental cell depending on the task version) and calculated the OPE slope with the regression method describe above. This procedure was repeated 5000 times. Based on the 5000 regression weights obtained in this way, the values corresponding with the 5th and 95th percentile were used to determine the confidence interval (i.e., the 90% CI) around the empirically observed OPE (i.e., the OPE slope estimated directly based on all available datapoints). An individual's OPE was reliable if this confidence interval did not contain the value 'zero'. In other words, this method tells whether an OPE can be observed in a given participant, no matter which of their reaction times are considered[2]. The relation between the

[2] As this approach resembles hypothesis testing, these intervals were called the 'H1 confidence intervals'. To ensure that the observed reliable OPE's were not due to chance, we also calculated the 'H0 confidence intervals'

OPE and MA is investigated using an independent sample Welch's t-test (the data of both groups were normally distributed, as indicated by a univariate Shapiro-Wilks test) to see whether as a group, those showing a reliable left-to-right OPE differed in MA compared to those who did not show an OPE. (3) In a final series of analyses, we further checked whether the subjects who spatialize also have a higher verbal and spatial WM capacity, better numerical order judgement abilities and higher math scores. Because the data of these tasks were not normally distributed in one or both subgroups (determined by the univariate Shapiro-Wilks test) the Mann-Whitney U test was used to check for group differences. For all analyses, effect-sizes are reported (i.e., Cohen's d for the independent Welch's t-test and the rank biserial correlation for the Mann-Whitney U test).

RESULTS

Descriptive statistics

In total, the OPE was determined for 114 participants. On average they judged 80% (SD=16%) of the sequences correctly in Phase 3, followed the go-no-go instructions correctly on 91% (SD=8%) of the trials, and correctly categorized the probes in 68% (SD=7%) of the go-trials. The overall reaction times was 890ms (SD=112ms). At the group level, an significant OPE was observed *[t(113)=-3.965, p<.001, d=.371]* (average slope=-15.119; SD=40.928). In addition, using the bootstrapping, 26 reliable left-to-right coders, 9 reliable right-to-left coders and 79 not (horizontal) spatial coders were identified. Only one of the right-to-left coders was familiar with a right-to-left oriented language. Because of the small sample size, and since we do not have a-priori theoretical predictions, the group of reliable right-to-left mappers were not considered in the analyses, however, their data is available in the shared data-file. A further overview of the performance of the other tasks can be found in Table 1. As can be seen there, at the group level, all tasks are conducted well above chance level and do not indicate floor or ceiling effects.

==== INSERT TABLE 1 HERE ====

(see ref. 30 for more details). Virtually the same pattern of results was found when the analyses reported below were repeated with the "H0-groups".

Table 1 Descriptive statistics of the overall task performance

	Valid	Missing[3]	Mean	Std. Deviation	Minimum	Maximum
AMAS	135	2	2.573	0.886	1	5
Ordinal position task						
Reaction times (ms)	114	23	890	112	653	1163
Slope (ms)	114	23	-15.199	40.928	-115.600	110.639
Backward digit span	94	2	10.511	3.513	4	20
Corsi-blocks	95	1	10.558	2.230	6	16
Order judgement						
Reaction times (ms)	95	1	1057	251	688	2005
Accuracy (%correct)	95	1	90.1%	4.6%	67.9%	98.4%
Math task	134	3	37.8%	14.3%	14.0%	77.0%

Replicating findings on the relation between Math Anxiety and cognitive performance

Replicating previous findings, the analyses revealed significant correlations in the expected direction between MA and the backward digit span *[Spearman r(93)=-.285, p= .006]*, the Corsi-blocks *[Pearson r(94)=-.279, p=.006]*, numerical order judgement *[Spearman r(94)=.522, p<.001]* and math performance *[Pearson r(132)=-.510, p<.001]*. Thus, higher math anxiety was linked to lower backward digit span, lower scores in Corsi blocks, longer reaction times in numerical order judgment (thus here the correlation is positive), and lower math performance. As anticipated [30,32], the (Spearman) correlation between the AMAS and the OPE correlation was not observed *[r(104)=.089, p=.369]*.

Math Anxiety and the spatial coding of serial order in verbal WM

Subsequent analyses reveal a link between spatial coding of serial order in verbal WM and MA: The group of reliable (left-to-right) spatial coders showed lower levels of MA (AMAS=2.098; SD=.648; n=25) compared to those who do not systematically use (horizontal) space to code serial order in verbal WM (AMAS=2.546; SD=.811; n=79) *[Welch's t(49.906)=2.830, p=.007, d=0.611]*.

[3] Missing values were due to technical issue (computer crashes) or due to empty cells in the experimental design (for the OPT).

Spatial coding of serial order, WM capacity, ordering abilities and mathematics

Final analyses reveal that spatial coding of serial order in verbal WM is associated to better performance in terms of verbal WM capacity, numerical order judgement and mathematics (see Figure 1). For the math task, the average score of the spatial coders was 47% (SD=15%) while the average score of the not-spatial coders was 38% (SD=14%) *[Mann-Whitney U= 626.000, p=.004, effect-size=.383]*. For the backward digit span, the average score of the spatial coders was 12.632 (SD=4.044) and for the not-spatial coders 10.442 (SD=2.913) *[Mann-Whitney U=314 p=.019, effect-size=.364]*. For the number ordering task, the average score of the spatial coders was 916ms (SD=174) and for the not-spatial coders 1089ms (SD=258) *[Mann-Whitney U =741.000, p=.006, effect-size .425]*. No differences were found for the Corsi-task [*Mann-Whitney U=546.500, p=.740, effect-size=.0425]*.

==== INSERT FIGURE 1 HERE ====

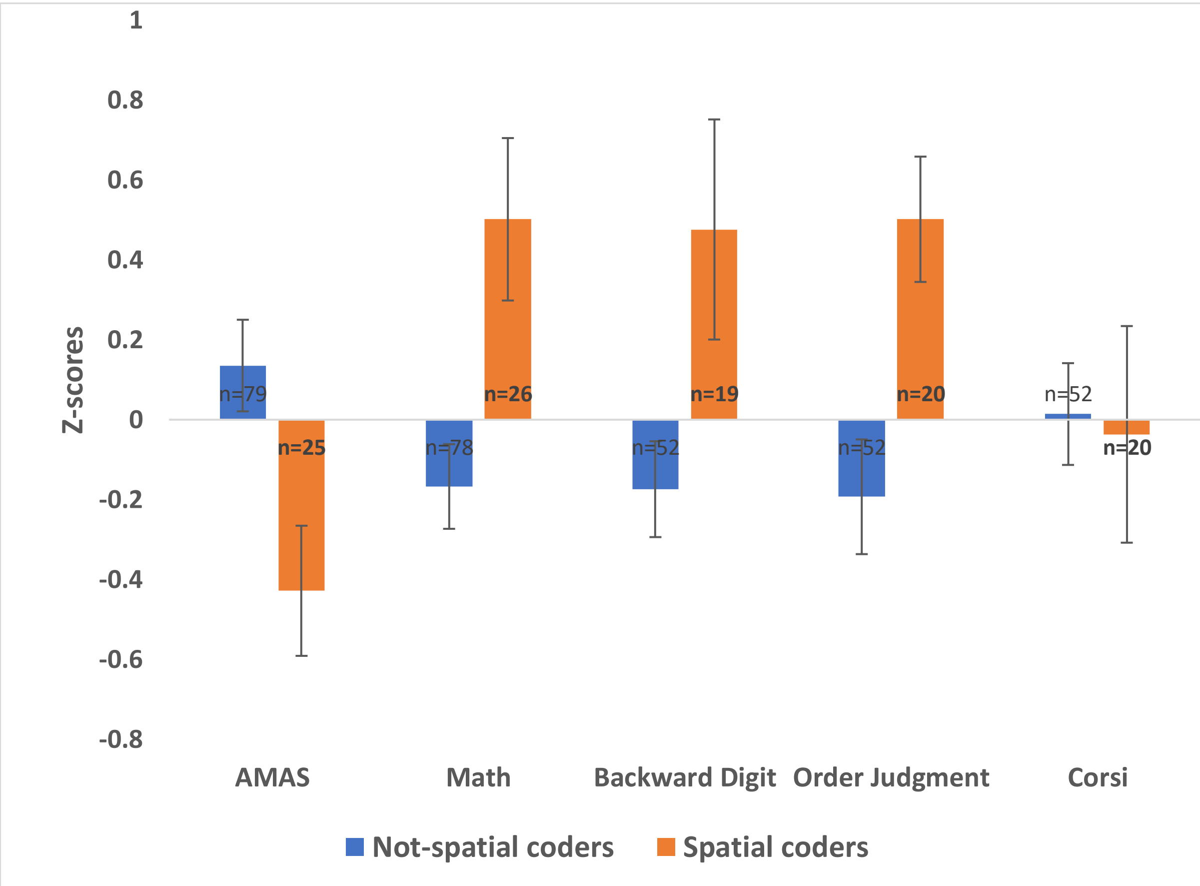

Figure 1: Comparison of the performance of spatial and not-spatial coders.

The performance is expressed in z-scores. The scores are recoded so that for each questionnaire/task a higher average indicates a higher score. Error bars indicate the standard error of measurement. The values in the bars indicate the sample size on which the average is calculated. Please note that z-scores are used only for presentation purposes in the Figure 1, and actual comparisons were conducted on untransformed scores.

GENERAL DISCUSSION

Besides replicating previous findings on the relation between MA and reduced verbal and visuo-spatial WM capacity, numerical order judgement abilities and math performance, we here show for the first time that MA is related to the spatialization of serially stored information in verbal WM. The main finding is that individuals who organize sequences of verbal information in a left-to-right manner in WM, report lower levels of MA. As such, this study shows that besides WM capacity [9], the spatial coding serial order in verbal WM can be an additional explanatory factor for MA. In addition, we found that those subjects who spatialize verbal sequences in WM have a higher verbal WM capacity and are better in numerical order judgement and in mathematics. These latter findings indicate that such spatialization is associated with better WM performance, and this not only in tasks that are close to the task used to measure the spatialization, but also in tasks that uses these WM resources (like math tasks). At this point however, we cannot definitively conclude anything about the underlying (causal) link between these processes (see below). However, as can be seen in Figure 1, the difference in performance between the spatial coders and not spatial coders is for each task around half a standard deviation in size, which is not trivial. This makes it worth the effort to further explore the causal relationships and if there are, to investigate whether positive and generalizable effects can be obtained when training this spatialization.

Taken together, the links between the spatialization of serial order in verbal WM, verbal WM capacity and numerical order judgment support the idea that spatial mechanisms play an important role in the coding of serial order both in LTM and WM [16]. Afterall, also in the backward digit span, order processing is a crucial component of the task. This raises questions why the spatialization is related to a higher WM capacity and better order coding? As WM traces decay, WM capacity depends on the proper maintenance of the memoranda. The ability to keep information in verbal WM depends on two (independent) mechanisms: articulatory rehearsal and attentional refreshing [41]. Where articulatory rehearsal is believed to be involved in the retention of acoustic information, attentional refreshing works by reactivating memory traces via attentional focusing to maintain them in WM. Evidence suggests that OPE has its source in attentional refreshing, because the OPE is insensitive to articulatory suppression and no OPE is found for items which can only be coded phonologically [42]. Additionally, behavioral and ERP findings indicate that the retrieval of serially stored items in verbal WM elicit shifts of spatial attention [24,43]. From these and other findings, the hypothesis has been put forward that spatial position markers are used by our cognitive system to code the serial order of items in verbal WM with a dedicated role for spatial attention when activating the memoranda within the resulting mental representation [44,45]. In this context it seems obvious that organizing WM in a systematic spatial fashion is beneficial for WM capacity and the maintenance of serial order [26]. Afterall, when our cognitive system spontaneously generates an internal spatial template to which the memoranda are bound in a systematic fashion, the resulting spatial configuration can be easily reactivated and automatically reflects the serial order of the memoranda. To our knowledge, this idea only received indirect support from observations that performance on the backward digit span, (a task which cannot be solved purely by articulatory rehearsal) can be disturbed by a visuo-spatial dual task [e.g., 46]. Our finding that spatialization in verbal WM is related to the score on the backward digit span, thus adds to the growing body of literature that visuo-spatial processes might be important for verbal WM and provides a (careful step toward) a more mechanistic explanation for the link between (verbal) serial order and space. An interesting observation in this respect is that the OPE does not seem to be related to visuo-spatial WM capacity. There are several potential explanations that need further investigation. For example, research on the forward and backward Corsi tasks suggests that the forward version (the one we used here) taps less on serial order processing, since this task is less impacted by a dual-task tapping on order coding [47]. This makes it worth exploring whether the absence of a relation reflects the known dissociation between explicit and implicit spatial processing [48] or between visuo-spatial or conceptual coding of space [49]. Afterall, in principle the OPE (and thus serial order coding in verbal WM) could reflect an implicit conceptual coding of space, while the spatial coding of the Corsi task would be (more) explicit and visuo-spatial in nature.

The link between spatialization of verbal WM, MA and mathematics is also reminiscent to large literature on the relation between mathematics and spatial abilities [50]. To explain this relationship, four potential (not mutually exclusive) explanations have recently been put forward [51]: (1) the spatial mental representation of numbers (i.e., the mental number line), (2) shared neural circuits, (3) the use of spatial visualization in mind and (4) the role of spatial working memory. Studies on MA can be informative to validate and extend some of these explanations. For example, the higher degree of spatial coding of numbers in subjects with high MA [52] goes against the idea that mentally representing numbers in a spatial manner is a characteristic of a performant mathematical brain (explanation 1). The lower spatial abilities of high MA subjects[53], on the other hand, are in line with the third explanation. The results of the current study, on the other hand, suggest that the 4th explanation can be extended, by assuming that the spatial coding of verbal WM can also be informative for the link between math and spatial abilities.

Previous observations indicate that the cognitive deficits in high MA subjects are larger when the tests contained numbers. For example, estimates of WM capacity in high MA subjects are lower when measured with digits compared to letters [54]. These finding suggests that (in high MA subjects) the exposure to numerical information can be sufficient to trigger an emotional response (with a negative impact on task performance). Although the backward digit span and the numerical order judgment task contained numbers as stimuli, this was not the case for the ordinal position task. In this task, the stimuli were written words referring to fruits and vegetables and nowhere in the task any reference to numbers was made. In other words, the relation between the spatialization of verbal WM and MA is unlikely be due to emotional reactions elicited by the stimuli. Additionally, although the participants were aware that they participated in a study about the cognitive underpinnings of mathematics, the OPT (and the other cognitive tasks) were always administered before the math test and the AMAS. As such, it is unlikely that the observed results are caused by a depletion/ taxation of cognitive resources due to worrisome thoughts induced when solving the math problems [55].

Finally, our subjects could also have suffered from test anxiety and theoretically it is possible that our results are not MA specific. Because no measure of test anxiety was included in our study, we cannot fully rule out this possibility. It is true that MA and test anxiety are related, but e.g., Hembree [56] found that both constructs only share around 37% of variance. For this reason, the current consensus is that MA can be considered as a separate construct (for a similar conclusion see also [4]). Therefore, we believe it is very likely that our results are specific to MA. It would however be interesting to investigate whether our results would generalize to more general cases of (test) anxiety, especially in tasks and contexts which also draw upon WM resources.

It is important to stress that our study does not provide evidence for a causal link between MA and spatialization. One way to investigate such a causal link, is to set up a training study to see whether improving the degree of spatialization of WM in a subject would result in a decrease of MA. Several training and coaching programs exist to lower MA (for an overview see [57]). To our knowledge however, none of these training programs directly tackle the cognitive functions that are associated to MA. This is in sharp contrast with the large amount of cognitive training programs that exist to improve mathematical abilities. In the context of WM, several training programs were tested. Unfortunately, the effect sizes of such training programs (if there are any) are small, and it is desirable to find paradigms that would enhance the effect of these programs (e.g. [58,59]). An interesting question arising from the current study is whether a targeted training of a well-defined processing component, i.e. the spatialization of serial order, will lead to improvement in mathematical abilities and to more generalizable effects. Afterall, having a more performant mental workspace will (likely) contribute to better task performance and (on the longer run) to more self-confidence. As such, future research will have to determine whether, in addition to the traditional approaches, such spatial training would be helpful alleviate the downward negative spiral caused by negative self-confidence, bad math performance and/ or rumination, which is characterizing many people affected by high MA.

Taken together, the current study shows that besides WM capacity, also the spatialization of serial order in verbal WM can be a novel cognitive correlate of the MA. Given the other WM-related benefits in the group people who spatialize verbal sequences in mind, we interpret this spatialization as an index of WM efficiency. This opens new directions for investigating causal links between spatialization and math performance and MA. In more general terms, this study also provides a nice illustration on how elementary cognitive processes are linked to the emotional / affective side of human functioning.

AUTHOR CONTRIBUTIONS

W.F. and J.-P.v.D. (in alphabetical order) developed the study concept and contributed to the study design. The experiment was programmed by J.-P.v.D. and data collection was performed under his supervision. J.-P.v.D. conducted the data analyses. K.C, W.F., and J.-P.v.D. (in alphabetical order) contributed to the theoretical framework. J-P.v.D. and K.C. drafted the final manuscript, and K.C. W.F., and J-P.v.D. (in alphabetical order) provided critical revisions and approved it. J.-P.v.D. accepts responsibility for the integrity of the data analyzed.

COMPETING INTERESTS

The authors declare no competing interests.

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