Spatial and numerical processing in children with high and low visuo-spatial abilities

Word count (text + references): 9308

Abstract

In the literature on numerical cognition, a strong association between numbers and space has been repeatedly demonstrated. However, only a few recent studies have been devoted to examine the consequences of low visuo-spatial abilities on calculation processing. In this paper, we wanted to investigate whether visuo-spatial weakness may affect pure spatial processing as well as basic numerical reasoning. In order to do so, the performances of children with high and low visuo-spatial abilities were directly compared on different spatial (the line bisection and Simon tasks) and numerical tasks (the number bisection, number-to-position and numerical comparison tasks). Children from the low visuo-spatial group presented the classic Simon and SNARC effects but showed larger deviation errors as compared to the high visuo-spatial group. Our results therefore demonstrated that low visuo-spatial abilities did not change the nature of the mental number line but rather led to a decrease in its accuracy.

Word count (abstract): 148

Keywords: numerical cognition; spatial representation; visuo-spatial difficulties.

1. Introduction

In the literature on numerical cognition, it has been suggested that humans and non-human animals present two distinct elementary systems for representing numerosities. One of these is precise and limited by its absolute set size (up to 3 or 4) (e.g., Scholl, 2001; Trick & Pylyshyn, 1994; Uller, Huntley-Fenner, Carey, & Klatt, 1999); the other is extensible to very large quantities and allows the discrimination and approximate representation of large visual and auditory numerosities without verbal counting (Butterworth, 1999; Dehaene, 1992; Feigenson, Dehaene, & Spelke, 2004; Nieder & Miller, 2003; 2004; Wynn, 1995).

The most widespread model used to account for this approximate number system is the mental number line hypothesis. According to this model, the representation of numerosities presents two major features reflecting the fact that numerical processing obeys Weber's law (Dehaene, 2001). First, numbers are represented on the mental number line by equal distributions of activation[1]. Therefore, the larger the distance between the quantities being compared, the more distant their distributions of activation on the mental number line and the easier it is to discriminate between them (i.e., distance effect; Buckley & Gillman, 1974; Dehaene, 1996; Gallistel & Gelman, 1992 ; Moyer & Landauer, 1967; van Oeffelen & Vos, 1982). Second, the mental number line is logarithmically scaled[1], so that small numerical magnitudes are further apart on the number line than large numerical magnitudes. For equal numerical distance, discrimination of two numerosities therefore worsens as their numerical size increases (i.e., the size effect; Aschcraft & Battaglia, 1978; Buckley & Gillman, 1974; Gallistel & Gelman, 1992; Moyer & Landauer, 1967; van Oeffelen & Vos, 1982).

A developmental transition from logarithmic to linear numerical representation has however been documented in several studies, suggesting that children's representation of numbers changes over time with age and increasing numerical experience (Berteletti, Lucangeli, Piazza, Dehaene, & Zorzi, 2010; Booth & Siegler, 2006; Siegler & Booth, 2004; Siegler & Opfer, 2003). In these studies, children and adults had to place different numbers on a visual number line with 0 at one end and either 10, 20 (Berteletti et al., 2010), 100 (Siegler & Booth, 2004) or 1000 (Booth & Siegler, 2006; Siegler & Opfer, 2003) at the other end. All these studies reported consistent results: the youngest children (e.g., second graders) positioned numbers logarithmically when the experimental condition was unfamiliar (e.g., 1000) but positioned them linearly when the experimental condition was familiar (e.g., 100). In contrast, older children and adults positioned numbers linearly in both experimental conditions. The dissociation between familiar and unfamiliar conditions therefore reveals that children's performance changes with age and shifts from a logarithmic to a linear representation. Interestingly, the linearity of the numerical representation appeared to be correlated to mathematical achievement (Booth & Siegler, 2008; Siegler & Booth, 2004).

In addition to obeying Weber's law, the mental number line is also thought to be spatially oriented. Much of the evidence used to support the fact that numbers and space interact with each other comes from studies that used the numerical counterpart of two spatial tasks: the Simon effect and the line bisection task. The Simon effect, on the one hand, refers to the fact that the response to a stimulus is faster and more accurate when the position of the stimulus is compatible with the side of the response (e.g., Simon, 1969; Simon & Rudell, 1967; Simon & Wolf, 1963). In a typical Simon task, participants see lateralized coloured stimuli and are instructed to respond with a left-side response key to one colour and with a right-side response key to the other colour. Although the stimulus location is completely irrelevant to the task, participants' reaction times are faster on spatially corresponding trials (left stimulus position – left side response and right stimulus position – right side response) than on spatially non-corresponding trials (left stimulus position – right side response and right stimulus position – left side response). Several studies provided evidence of a similar compatibility effect between number and space. The so-called SNARC effect (Spatial Numerical Association of Response Codes) indicates that (in occidental cultures) small numbers are preferentially responded to the left whereas larger numbers are preferentially responded to the right (Dehaene, Bossini, & Giraux, 1993). As with the Simon effect, the SNARC effect appears even if participants cross their hands, indicating that both effects originate from the mapping of an input stimulus onto an allocentric frame of reference (for the Simon effect: see Röder, Kusmierek, Spence & Schicke, 2007; for the SNARC effect, see Dehaene et al., 1993; but see Wood, Nuerk, & Willmes, 2006).

The other task is the line bisection task. This task has been widely used to investigate spatial attention and requires participants to bisect a line into two parts of equal length by marking its subjective midpoint with a pencil. While patients with right-hemispheric lesions deviate to the right of the objective midpoint (left hemineglect), normal right-handed people tend to systematically bisect lines slightly to the left of the objective midline (pseudoneglect effect; Jewell & McCourt, 2000). Several studies provided evidence that similar patterns of attentional bias occurred in the numerical domain (Priftis, Zorzi, Meneghello, Marenzi, & Umiltà, 2006; Vuilleumier, Ortigue, & Brugger, 2004; Zorzi, Priftis, & Umiltà, 2002). These studies used the number bisection task: when required to indicate (without calculating) the number midway between two others, control participants tend to respond with numbers smaller than the true midpoint (Cattaneo, Fantino, Silvanto, Tinti, & Vecchi, 2011) while right hemispatial neglect patients tend to display a “rightward” bias and thus produce numbers larger than the true midpoint (Zorzi et al., 2002).

Given the above-reviewed data on the interactions between number and space, it is not surprising that visuo-spatial problems have often been supposed to induce mathematics difficulties (Rourke & Conway, 1997). NVLD children, who are characterized by intact verbal abilities but impaired visuo-spatial abilities (Mammarella & Cornoldi, 2014; Nichelli

& Venneri, 1995; Rourke, 1989) perform for example significantly worse than typically developing children in geometry (Mammarella, Giofrè, Ferrara, & Cornoldi, 2013) and written calculation (Mammarella, Lucangeli, & Cornoldi, 2010; Venneri, Cornoldi & Garuti, 2003). Yet, beyond those difficulties in mathematical tasks that directly imply visuo-spatial processes, one may wonder whether poor visuo-spatial skills in children might also be related to peculiarities in number magnitude representation itself as this has a spatial component as well. Currently, only one study has approached this question. In that study, Bachot, Gevers, Fias, and Roeyers (2005) tested the presence of a SNARC effect in a group of children who presented both NVLD and difficulties in mathematics and found that no SNARC was present. However, as this group of children was selected as presenting both NVLD and math difficulties, we cannot establish whether the absence of a SNARC effect was due to the math difficulties or to the NVLD.

The present paper aims to investigate whether developmental visuo-spatial weaknesses in children may affect not only pure spatial processing but also basic numerical tasks tapping the spatial aspects of number magnitude. To do so, 4^{th} grade children were recruited to participate in the study. They were first required to perform three visuo-spatial tasks: the NEPSY design copying test (Korkman, Kirk, & Kemp, 1998), the Rey Complex Figure Test (Osterrieth, 1944) and the Cornoldi shortened visuo-spatial questionnaire (Cornoldi, Venneri, Marconato, Molin, & Montinari, 2003). These 3 measures were chosen because they are quick, reliable, and valid instruments to identify low visuo-spatial abilities in primary school. On the basis of their scores in these 3 visuo-spatial measures, children were categorized as presenting low or high visuo-spatial skills. Both groups of children were then asked to perform two spatial tasks (the line bisection and the Simon tasks) and three numerical tasks (number-to-position, number bisection and numerical comparison task to 5).

These different tasks allowed us to investigate several hypotheses regarding the strengths and weaknesses of children presenting low visuo-spatial abilities. First, we studied whether low visuo-spatial abilities only affect pure spatial processing (line bisection and Simon tasks) or whether it also affect basic numerical tasks tapping the spatial aspects of number magnitude (number-to-position, number bisection and numerical comparison task to 5). Second, we examined whether low visuo-spatial abilities affect explicit (line bisection task) as well as implicit spatial processing (Simon effect). Third, we investigated whether low visuo-spatial abilities differently impact external and internal numerical processing. This kind of dissociation has already been observed in the spatial field with patients presenting hemispatial neglect (Hillis & Rapp, 1998; Ota, Fujii, Tabuchi, Sato, Saito, & Yamadori, 2003). Therefore, if low visuo-spatial children only present difficulties with external numerical processing, they should be impaired in the number-to-position tasks. They should not be impaired in the number bisection task. In contrast, if low visuo-spatial children also present difficulties with an internal representation, they should be impaired in both tasks. Finally, as children were required to perform the Simon and the numerical comparison tasks with their hands in parallel or crossed over the body midline, our experiment also allowed us to examine whether low visuo-spatial skills affect the development of an allocentric spatial frame of reference. According to recent studies, the use of this coordinate system develops during early infancy (Bremner, Holmes, & Spence, 2008) and depends on early visual experience (Collignon, Voss, Lassonde, & Lepore, 2009; Röder, Föcker, Hotting, & Spence, 2008; Röder et al., 2007; Röder, Rösler, & Spence, 2004). Indeed, while sighted participants presented classic Simon and SNARC effect in crossed and uncrossed hand conditions, early blind individuals showed the classic effects in the uncrossed condition and reversed effects in the crossed condition (Crollen, Dormal, Seron, Lepore & Collignon, 2013; Röder et al., 2007). In line with these data, we would like to investigate whether low visuo-spatial abilities prevent the use of the allocentric reference frame. If this is not the case, the classic Simon and SNARC effects should appear in both hand positions. In contrast, if low visuo-spatial abilities children preferentially use an egocentric coordinate system, as blind people do, reverse Simon (Röder et al., 2007) and SNARC effects (Crollen et al., 2013) should be observed in this group in the crossed-hand position.

2. Method

2.1 Participants

The parents of 70 middle-class French-speaking children gave written consent for the participation of their children in the study. These children were all in grade 4 and were not diagnosed as presenting NVLD. They were first required to perform two preliminary visuo-spatial tasks: the NEPSY design copying test (Korkman et al., 1998) and the Rey Complex Figure Test (Osterrieth, 1944) which are two copy drawing tasks that are typically poorly performed in the case of low visuo-spatial skills. Both tasks were performed collectively in the children's classroom. In addition, participants' parents were asked to complete the Cornoldi shortened visuo-spatial questionnaire (Cornoldi et al., 2003), which is a quick, reliable, and valid instrument that may be helpful in identifying children with visuo-spatial difficulties in primary school.

The mean Z-score of these three significantly correlated measures (see Table 1) was used to create two groups of participants. The high visuo-spatial group, hereafter called the high group, included the 25 children (18 girls; two left-handed; Mean age = 9.6 ± 0.58) who obtained Z-scores higher than the 65 percentile (M = 0.81 ± 0.25; range: 0.46 to 1.31). The low visuo-spatial group, hereafter called the low group, included the 25 children (14 girls; 6 left-handed; Mean age = 9.8 ± 0.71) who obtained Z-scores lower than the 35 percentile (M = -0.91 ± 0.44; range: -2.41 to -0.37). We choose the 35/65 percentiles in order to be able to have group differences at the visuo-spatial level, $t(48) = -17.09$, $p < .001$, while not only including the more extreme children.

Compared to published normative data, the low group had a mean standard score at the NEPSY design copying test of 5.64 (2.19) and the high group had a mean standard score of 10.84 (1.54) (NS of 10±3; Korkman et al.; 1998). For the Rey Complex Figure Test, the low group had a mean of 18.52 (1.72) and the high group had a mean of 31.44 (2.68). Scores of the low group were below the 10^{th} percentile; scores of the high group corresponds to the 58^{th} percentile (Osterrieth; 1944). For these 2 tests, the low group's performance was therefore lower than the general mean while the high group's performance was included within the normal range. Finally, for the Cornoldi shortened visuo-spatial questionnaire, the low group had a mean of 28.52 (4.34) and the high group a mean of 36.04 (2.96) which corresponds to z-scores of respectively -0.36 and 0.70 (Cornoldi et al., 2003). Parents' complaints were therefore weak for both groups of children.

After the selection phase, the 50 selected children were tested individually in a quiet room of their school and submitted to the five tasks presented below. The testing session lasted approximately one hour and a half.

Table 1. Correlations between the three preliminary visuo-spatial measures.

	REY	CORNOLDI
NEPSY	.42**	.47**
REY		.39**

** $p < .001$

2.2 Tasks

2.2.1 Line bisection task

The line-bisection task was composed of 18 horizontal black lines (α = .59) 1 mm wide presented on three different white sheets of paper (21 cm x 30 cm). Half of the lines measured 8 cm in length; the other half 16 cm. The lines were randomly positioned so that six lines appeared in the middle of the sheet, six lines appeared near the left margin, and six lines appeared near the right margin. The sheet was laid in front of the participant's midline. Participants were instructed to bisect all lines into two parts of equal length by marking the subjective midpoint of each line with a pencil. The experimenter covered each line after it was marked to ensure that participants were not biased by their previous choices. There were no time restrictions. The subjective midpoints of each marked line were carefully measured. To examine whether responses presented a left or a right bias, the deviation score (DS) for each line was computed as follows: participant's half estimation – true half. Negative values indicated a left bias; positive values a right bias. To measure the precision of the responses, the absolute DS for each child and for each trial was also computed and then averaged across the scores for each child.

2.2.2 Number bisection task

Eighteen pairs of numbers (α = .89) were visually presented to the children. Six pairs contained a one- and a two-digit number (e.g., 8-15); twelve other pairs included two two-digit numbers (e.g., 59-64). The two numbers of the pair were presented to the left and to the right of a fixation cross. The numerical distance between each number was either 5, 7 or 9. The magnitude of the numbers presented was either small, medium or large (see Table 2). Each number pair was presented twice, once in the ascending order (i.e., smallest number presented to the left of the fixation cross and largest number presented to the right of the fixation cross) and once in the descending order (i.e., smallest number presented to the right of the fixation cross and largest number presented to the left of the fixation cross); giving a total number of 36 items. The visual stimuli were presented by a computer positioned exactly in front of the participants and aligned with their body's midline. E-Prime (Psychology Software Tools, Pittsburgh, PA) was used to present the stimuli. Each trial began with the presentation of a fixation cross (500 ms). Two numbers then appeared left and right of the fixation cross and stayed on the screen until participants gave a response. Reaction times were collected. There was no time limit but children received the instruction to judge and orally report the numerical midpoint of the number pair as quickly as possible, without calculating. Experimenter noted children's responses. The deviation score (DS) for each number pair was calculated as follows: participant's number midline estimation – true midline. As in the previous task, negative values indicated a left bias and positive values indicated a right bias. The absolute DS was also computed. Four practice trials were given before starting the experiment.

Table 2. List of stimuli used in the number bisection task.

	Distance		
Magnitude	5	7	9
Small	9-14	8-15	9-18
	8-13	9-16	8-17
Medium	29-34	18-25	18-27
	18-23	29-36	29-38
Large	59-64	68-75	68-77
	68-73	59-66	59-68

2.2.3 Number-to-position task

The number-to-position task was composed of 20 horizontal black lines (α = .79) 1 mm wide and 23 cm in length. Each line was labelled "0" at its left end and "100" at its right end. The lines were presented in the middle of four different white sheets of paper (21 cm x

30 cm – five lines per page). The sheet was laid in front of the participant's midline. Children were told that they had to show where they thought different numbers would fall on the line by marking the location with a pencil. Half the numbers to position were smaller than 50 (i.e., 4, 8, 13, 17, 22, 26, 31, 36, 41, 45); the other half were larger (i.e., 55, 59, 64, 69, 74, 78, 83, 87, 92, 96). These numbers were randomly presented and written at the left of each line. The experimenter covered each line after it was marked to ensure that the participants were not biased by their previous responses. There were no time restrictions. The deviations to the true number's position were carefully measured. The DS for each number was computed as follows: participant's number estimation – true number. Negative values indicated a left bias, positive values a right bias. The absolute DS was computed as well.

2.2.4 Simon task

In this task, participants were asked to judge whether a visually presented rectangle was either red or green. The stimuli were presented by a computer positioned exactly in front of the participants and aligned with their body's midline. The target rectangles appeared to the left or to the right of a fixation cross. Participants were instructed to respond as quickly and accurately as possible in a forced two-choice paradigm by pressing one of two response keys placed 20 cm in front of each participant's body and 10 cm away from the body midline in the left and right hemi-spaces. The task comprised two response assignments. In the first one, "green rectangle" was assigned to the left response key, while "red rectangle" was assigned to the right response key. In the second condition, the reverse assignment was used: the "red rectangle" was assigned to the left key and the "green rectangle" to the right key. To aid understanding of the instructions, response keys were coloured in green and red. Children were therefore told to press the response key which had the same colour as the rectangle presented. Children were moreover required to perform the task either with their hands in a parallel posture (i.e., uncrossed posture) or with their arms crossed over the body midline so that the left hand was on the right response key and the right hand was on the left response key (i.e., crossed posture). Each child completed four blocks of trials [response mode (2) x posture (2)]. Each block included 16 congruent trials (i.e., children had to press the response key which was on the same side as the target rectangle) and 16 incongruent trials (i.e., the target rectangle was not presented on the same side as the appropriate response key), giving a total number of 128 trials. The order of response mode and posture conditions was counterbalanced across participants. Stimuli were delivered and reaction times were recorded using E-Prime software (Psychology Software Tools, Pittsburgh, PA). Each trial began with the presentation of a fixation cross for 500 ms. A green or a red rectangle then appeared left or right of a fixation cross until participants gave a response. The inter-stimuli interval ranged from 800 to 1200 msec. Eight practice trials were given before beginning the task and eight other practice trials were given before changing hand posture.

2.2.5 Numerical comparison task

In this task, participants were asked to judge whether an Arabic digit was smaller or larger than 5. The Arabic digits used were numbers 1-9 (except for 5). Participants were instructed to respond as quickly and accurately as possible in a forced two-choice paradigm by pressing one of two response keys placed 20 cm in front of each participant's body and 20 cm away from the body midline in the left and right hemi-spaces. The task comprised two response assignments. In the first condition, the "smaller than 5" response was assigned to the left response key, while the "larger than 5" response was assigned to the right response key. In the second condition, the reverse assignment was used: the "larger than 5" response to the left key and the "smaller than 5" response to the right key. To aid understanding of the instructions, small and large snowmen were associated to the appropriate response key. Children were moreover asked to perform the task either with their hands in a parallel posture (i.e., uncrossed posture) or with their arms crossed over the body midline. Each participant completed 4 blocks of trials [response mode (2) x posture (2)]. The order of response mode and posture conditions was counterbalanced across participants. Stimuli were delivered and reaction times were recorded using E-Prime. Each Arabic digit was presented eight times in each condition, giving a total of 192 stimuli [number (8) x presentation (6) x response mode (2) x posture (2)] randomly presented in four experimental blocks. Each trial began with the presentation of a fixation cross for 500 ms. An Arabic number between 1 and 9 (except 5) then appeared in the centre of the computer screen and remained on the screen until participants responded. The inter-stimuli interval ranged from 800 to 1200 msec. Eight practice trials were given before starting the experiment and before changing the hand posture.

3. Results

3.1 Line bisection task

In order to examine children's left or right bias, the DS were first submitted to a one-sample t-test with 0 as the reference value. The pseudo-neglect effect was not significant in the high group (M = -0.07 ± 0.05), $t(24) = -1.46$, $p > .1$, while it was observed in the low group (M = -0.16 ± 0.05), $t(24) = -2.91$, $p < .01$. However, when compared to each other, both groups did not differ, $t(48) = 1.25$, $p > .2$.

To investigate children's precision, a 2 (length: 8 cm vs. 16 cm) x 2 (group: high visuo-spatial vs. low visuo-spatial) repeated measures ANOVA was performed on the absolute values of the DS (│DS│). The length effect was significant, $F(1, 48) = 59.31$, $p < .001$, $\eta^2 = .55$, as well as the group effect, $F(1, 48) = 4.88$, $p < .05$, $\eta^2 = .09$. Children's accuracy was lower in the 16 cm-line condition (M = 0.49 ± 0.03) than in the 8 cm-line condition (M = 0.30 ± 0.02). More importantly, children from the low visuo-spatial group were less accurate (M = 0.45 ± 0.04) than children in the high visuo-spatial group (M = 0.34 ± 0.04). The group x length interaction was not significant, $F(1, 48) = 1.68$, $p > .2$, $\eta^2 = .03$.

3.2 Number bisection task

Responses that were outside the numerical interval were excluded from all the following analyses (1.76% of the data in the high group and 5.55% of the data in the low group, $\chi^2(1) = 69.66$, $p < .001$. More outliers were moreover observed in the descending order than in the ascending order, $\chi^2(1) = 59.201$, $p < .001$).

The DS were first submitted to a one-sample t-test (reference value = 0) in order to examine whether children's responses were under- or over-estimated. The pseudo-neglect effect was observed in the high group ($M = -0.25 \pm 0.09$), $t(24) = -2.62$, $p < .05$, while it was not in the low group ($M = -0.24 \pm 0.14$), $t(24) = -1.76$, $p = .09$. However, when compared to each other, both groups did not differ, $t(48) = -0.05$, $p > .9$.

Then, to analyse the precision of children's responses, a 3 (magnitude: small, medium and large) x 3 (distance: 5, 7, and 9) x 2 (order: ascending vs. descending) repeated measures ANOVA was performed on the $|\text{DS}|$, with group as the between-subject factor. A distance effect was first highlighted, $F(2, 88) = 75.04$, $p < .001$, $\eta^2 = .63$: larger the numerical interval presented, larger the errors committed (all $p_s < .001$). More importantly, there was a main effect of group, $F(1, 44) = 11.02$, $p < .01$, $\eta^2 = .20$, indicating that the high visuo-spatial group ($M = 0.88 \pm 0.07$) was more accurate than the low visuo-spatial group ($M = 1.23 \pm 0.08$); and a distance x group interaction, $F(2, 88) = 4.05$, $p < .05$, $\eta^2 = .08$. In order to decompose this interaction, regression equations were fitted for each participant separately (Lorch & Myer, 1990). The coefficients then obtained in each group were compared and submitted to a paired samples t-test which revealed that the slope of the distance effect was larger in the low visuo-spatial group ($ß = .23 \pm .15$) than in the high visuo-spatial group ($ß = .15 \pm .10$), $t(44) = -2.15$, $p < .05$, Cohen's d = 0.65 (see Figure 1).

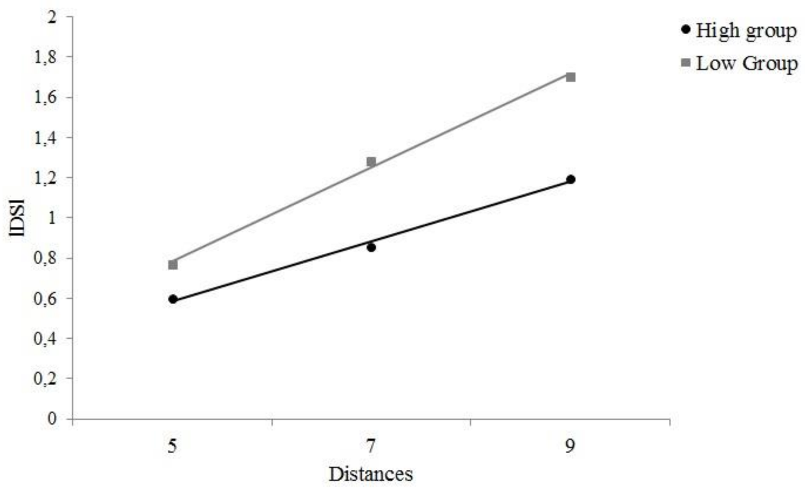

Figure 1. Slope of the distance effect in the number bisection task for the high and low visuo-spatial groups.

3.3 Number-to-position task

The children's DS were submitted to a one-sample t-test in order to examine whether children's responses were under- or over-estimated. The pseudo-neglect effect was observed in both groups, $t(24) = -3.57$, $p < .001$ in the high group, $t(24) = -2.44$, $p < .05$ in the low group, $t(48) = -1.13$, $p > .2$.

A repeated measures ANOVA, with magnitude (small vs. large) as within-subject factor and group (high vs. low) as between-subject factor, was carried on the $|\text{DS}|$. This analysis revealed a significant effect of group, $F(1, 48) = 14.96$, $p < .001$, $\eta^2 = .24$: children in the high visuo-spatial group were more accurate ($M = 5.14 \pm 0.47$) than children in the low visuo-spatial group ($M = 7.73 \pm 0.47$). No other effects were highlighted.

Other analyses were conducted to compare the fit of linear and logarithmic models to the median estimates of the target numerical values. As shown in Figure 2, children's estimates fit the linear model better than the logarithmic one. In both groups, the logarithmic equation accounted for 82% of the variance, whereas the best-fitting linear equation accounted for 99%, $t(19) = -6.38$, $p < .001$ in the high visuo-spatial group; $t(19) = -5.45$, $p < .001$ in the low visuo-spatial group.

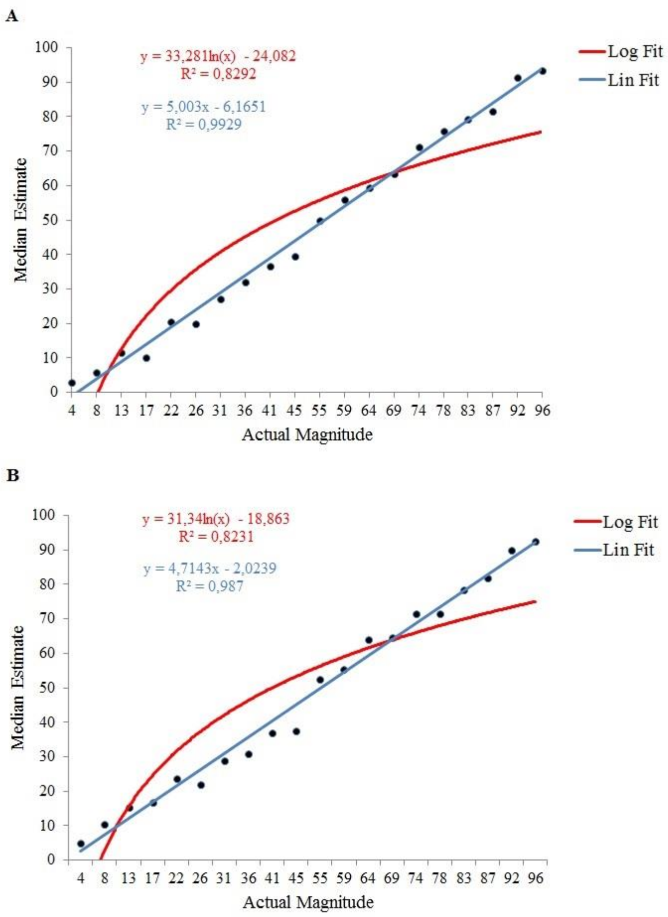

Figure 2. Logarithmic and linear fitting of the number-to-position task in the (A) high visuo-spatial group and (B) low visuo-spatial group.

3.4 Comparison of the line bisection, number bisection and number-to-position tasks

In the line bisection task, the pseudo-neglect effect was observed in the high group but not in the low group. In the number-to-position task, the inverse was true. Finally, in the number bisection task, the pseudo-neglect effect was observed in both groups. As the line bisection, number bisection and number-to-position tasks' performances were also measured in terms of ∣DS∣, a further analysis was conducted to examine whether the groups' difference was larger in task requiring the processing of external space (line bisection), the mapping of number magnitude on external space (number-to-position) or the internal processing of number magnitude (number bisection). To that aim, the ∣DS∣ of each child was transformed into z-scores for each of the three tasks. The measures obtained in each task were then submitted to a 3 (Tasks: line bisection, number bisection, number-to-position) x 2 (Groups: low vs. high) repeated measures ANOVA with group as the between-subject factor. This analysis revealed a significant effect of group, $F(1, 47) = 33.29$, $p < .001$, $\eta^2 = .41$. There was no effect of task, $F(2, 94) = 0.009$, $p > .9$, $\eta^2 = .00$, and no group x task interaction, $F(2, 94) = 0.39$, $p > .6$, $\eta^2 = .008$, suggesting that children with low visuo-spatial abilities were equally less accurate that those with high-visuo-spatial abilities in those three tasks.

3.5 Simon task

To analyse the accuracy scores (i.e., number of correct responses) in the Simon task, a Group (high vs. low) x Condition (congruent vs. incongruent) x Posture (crossed vs. uncrossed) repeated measures ANOVA was calculated with group as a between-subject factor. This only showed a main effect of condition, $F(1, 48) = 8.25$, $p < .01$, $\eta^2 = .15$, and a posture x condition interaction, $F(1, 48) = 4.39$, $p < .05$, $\eta^2 = .08$. There was no main effect of group, $F(1, 48) = 1.03$, $p > .3$, $\eta^2 = .02$. Overall, children were more accurate in the congruent condition ($M = 63.02/64 \pm 0.15$ than in the incongruent one ($M = 62.32/64 \pm 0.22$). The interaction indicated that the difference between the congruent and incongruent conditions was significant in the crossed position, $t(49) = 3.41$, $p = .001$, but was not significant in the uncrossed posture, $t(49) = 0.61$, $p > .5$.

A similar analysis was performed on median reaction time (RT) expressed in ms. A main effect of posture was highlighted, $F(1, 48) = 63.81$, $p < .001$, $\eta^2 = .57$. Children responded faster when their arms were in the uncrossed posture ($M = 638.62 \pm 13.78$) in comparison to when their arms were crossed over their body midline ($M = 724.02 \pm 16.63$). The congruency condition was also significant, $F(1, 48) = 30.05$, $p < .001$, $\eta^2 = .38$, indicating that congruent trials ($M = 664.97 \pm 14.68$) were responded to faster than incongruent ones (M

= 697.67 ± 14.55). There was no group effect, $F(1, 48) = 0.09$, $p > .7$, $\eta^2 = .002$ but a posture x condition x group interaction was observed, $F(1, 48) = 6.57$, $p =.01$, $\eta^2 = .12$. In the high visuo-spatial group, the posture, $F(1, 24) = 26.43$, $p < .001$, $\eta^2 = .52$, and congruency effects, $F(1, 24) = 13.02$, $p = .001$, $\eta^2 = .35$, were significant and did not interact with one another, $F(1, 24) = 0.76$, $p > .3$, $\eta^2 = .03$, suggesting that the Simon effect (i.e., larger RT in the incongruent trials by comparison to the congruent trials) was equally present in the crossed as well as in the uncrossed posture. In the low visuo-spatial group, there were also significant posture, $F(1, 24) = 44.34$, $p < .001$, $\eta^2 = .65$, and congruency effects, $F(1, 24) = 17.06$, $p < .001$, $\eta^2 = .42$, but the posture x congruency interaction was also highlighted, $F(1 , 24) = 7.06$, $p = .01$, $\eta^2 = .23$. Paired samples t-tests comparing the congruent and incongruent conditions in both postures demonstrated that low visuo-spatial children presented the Simon effect in the crossed position, $t(24) = -5.31$, $p < .001$, while the effect failed to reach significance in the uncrossed position, $t(24) = -1.68$, $p > .1$ (see Figure 3).

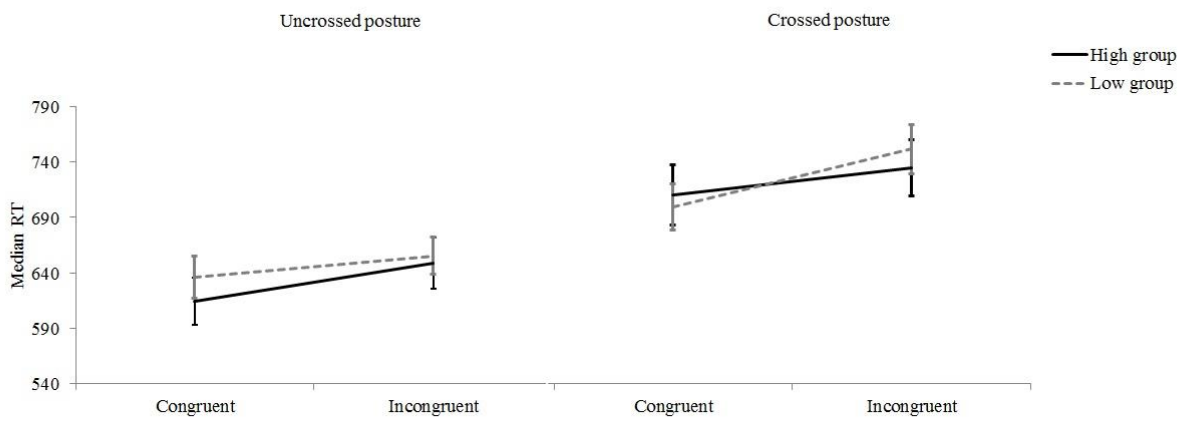

Figure 3. Results of the Simon task in both postures (uncrossed vs. crossed) and in both groups of children (high visuo-spatial vs. low visuo-spatial).

3.6 Numerical comparison task

In order to examine the precision of the mental number line, the distance effect was examined using a repeated measures ANOVA on accuracy scores (i.e., number of correct responses). This ANOVA was run on the 4 levels of the distance towards the reference number five (i.e., distance 1, 2, 3 and 4), the posture (uncrossed vs. crossed) and the group (high vs. low). It only showed a significant effect of distance, $F(3, 144) = 20.10$, $p < .001$, $\eta^2 = .29$: children were less accurate when the target number was close to the reference number five. There was no posture effect, $F(1, 48) = 0.10$, $p > .7$, $\eta^2 = .0020$. The group effect was marginally significant, $F(1, 48) = 3.01$, $p = .09$, $\eta^2 = .06$; the high visuo-spatial children tending to be more accurate ($M = 23.25/24 \pm 0.13$) than their low visuo-spatial peers ($M = 22.94/24 \pm 0.13$).

The same analysis was carried out on median RT. It showed a main effect of posture, $F(1, 48) = 25.81$, $p < .001$, $\eta^2 = .35$, and a main effect of distance, $F(3, 144) = 51.62$, $p < .001$, $\eta^2 = .52$. There was no main effect of group, $F(1, 48) = 0.02$, $p > .8$, $\eta^2 = .00$.

A last analysis was performed to measure the SNARC effect. For each child, for each magnitude (small: numbers 1-4; large: numbers 6-9) and for each side of response, median reaction time (RT) was calculated. Then, differences in RT (dRT) were computed from these median scores, subtracting left-sided responses from right-sided responses. dRT was then analyzed by a 2 (magnitude: small vs. large) x 2 (posture: crossed vs. uncrossed) repeated measures ANOVA with group (high vs. low) as between-subject factor. Results showed a main effect of posture, $F(1, 48) = 4.33$, $p < .05$, $\eta^2 = .08$, suggesting that dRT was more pronounced in the crossed posture ($M = 16.22 \pm 12.33$) in comparison to the uncrossed posture ($M = -9.07 \pm 9.24$). There was also a main effect of magnitude, $F(1, 48) = 8.11$, $p < .01$, $\eta^2 = .14$. Indeed, while a left-sided advantage was observed in the small magnitude range ($M = 54.40 \pm 22.30$), a right-sided advantage was observed in the large magnitude range ($M = -47.25 \pm 17.41$), which is the typical signature of the SNARC effect. There was no difference between groups of children, $F(1, 48) = 1.45$, $p > .2$, $\eta^2 = .03$. Moreover, as none of the interactions were significant, the SNARC effect (i.e., left-sided advantage for small numbers and right-sided advantage for large numbers) appeared to be present and similar in both postures and in both groups of children (see Figure 4).

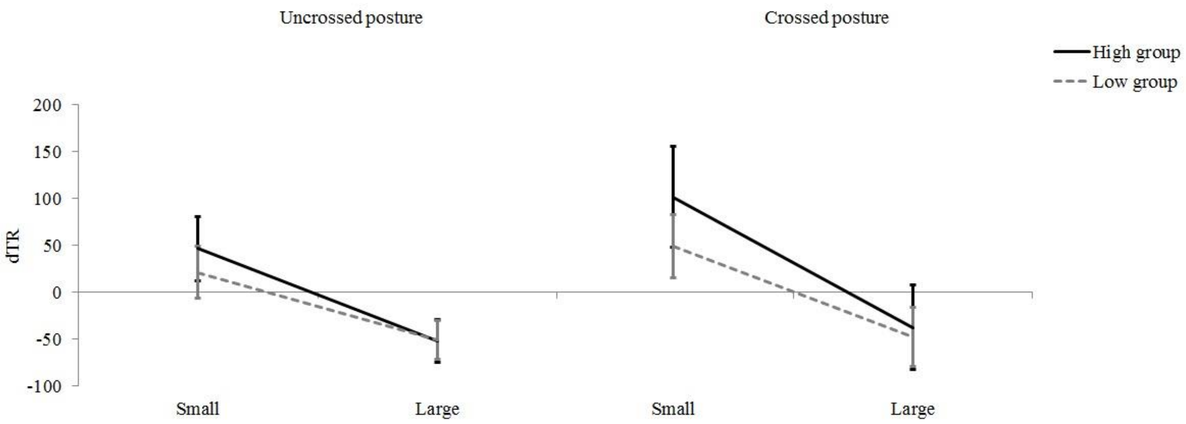

Figure 4. Data of the numerical comparison task in both postures (uncrossed vs. crossed) and in both groups of children (high visuo-spatial vs. low visuo-spatial).

4. General discussion

In the literature on numerical cognition, a strong association between number magnitude representation and space has been repeatedly demonstrated (see Hubbard, Piazza, Pinel, & Dehaene, 2005 for a review). However, only a few studies have been devoted to studying the consequences of low visuo-spatial abilities on number processing in children (e.g., Rourke & Conway, 1997). In this paper, performances of children with high and low visuo-spatial abilities were directly compared on different spatial (the line bisection and Simon tasks) and numerical tasks (the number bisection, number-to-position and numerical comparison tasks). We first investigated whether low visuo-spatial abilities only affect pure spatial processing or whether it also affects basic numerical processing. Overall, children from the high visuo-spatial group outperformed low visuo-spatial children in the line bisection as well as in the number bisection and number-to-position tasks. Interestingly, the accuracy differences observed between both groups were similar across the three tasks cited above, suggesting that low visuo-spatial abilities similarly affected spatial and numerical processing. In the Simon and SNARC tasks, in contrast, high and low visuo-spatial children demonstrated a similar level of performance. This result is probably due to the fact that the Simon and SNARC tasks involved a 2-forced choice paradigm which is by definition less error-prone than the free response testing design used in the line bisection, number bisection and number-to-position tasks. We could also consider that the line bisection requires the processing of metric or coordinate spatial relations while the Simon task relies on categorical spatial relations.

We secondly examined whether low visuo-spatial abilities affect explicit (line bisection task) as well as implicit spatial processing (Simon effect). Our results did not allow us to draw firm conclusions about the presence or absence of a dissociation between these 2 spatial processing. As we already stated, accuracy measures obtained in the line bisection task and in the Simon task were hardly comparable because these 2 experiments involved different kinds of experimental designs, a free response testing paradigm involving metric processing on the one hand and a 2-forced choice design involving categorical processing on the other hand. Moreover, while the low visuo-spatial children manifested the classic pseudo-neglect effect in the line bisection task, the Simon effect of these children was only demonstrated in the crossed posture but failed to reach significance in the uncrossed position. Conversely, the high visuo-spatial children did not manifest the pseudo-neglect effect in the line bisection task but presented the Simon effect in the uncrossed and crossed postures. The absence of the pseudo-neglect effect in the high group reflected a high level of accuracy. The absence of the Simon effect in the low group in the uncrossed posture, together with its presence in the crossed position, is not in accordance with the idea that low visuo-spatial children could present abnormal stimulus-response compatibility effects.

Third, we investigated whether low visuo-spatial abilities differently impact external and internal numerical processing. No dissociations were observed: high and low visuo-spatial children equally differed from each other in the number-to-position task as well as in the number bisection task. This means that children with low visuo-spatial skills perform less well than the high visuo-spatial children not only in numerical tasks that explicitly require the processing of external spatial dimensions but also in tasks that require to process the internal number magnitude representation.

Fourth, as children were required to perform the Simon and the numerical comparison tasks with their hands in parallel or crossed over the body midline, our experiment finally allowed us to examine whether low visuo-spatial skills affect the development of an allocentric spatial frame of reference. At the numerical level, high and low visuo-spatial groups actually demonstrated the SNARC effect in the uncrossed as well as in the crossed hands condition. The mental number line of both groups therefore seems to be oriented from left-to-right and children of both groups seem to preferentially map their responses to the allocentric space. Indeed, according to Wood et al. (2006), two relevant spatial frames of reference are available in stimulus-response association tasks: the egocentric and the allocentric frames of reference. Stimulus-response compatibility effects are therefore a weighted sum of the activation of both coordinate systems. As pointed out by Cho and Proctor (2003), stimulus-response compatibility depends on which frames of reference are activated in each experimental set: when hands are crossed, there is a conflict between both coordinates. If the saliency of both coordinates is approximately equal, a null stimulus-response compatibility effect is observed, since egocentric and allocentric associations are complementary. If the weights of both coordinates are unequal, a compatibility effect is observed in the direction of the coordinate system which is the most salient. As the Simon and SNARC effects were observed in the crossed hands position, it seems obvious that the allocentric coordinate system guided the behaviors of both the low and high visuo-spatial groups.

It is obvious that the Simon and SNARC effects share some important characteristics (Mapelli et al., 2003). Firstly, both refer to a spatial compatibility effect between the response location and an attribute of the stimulus (position or magnitude). Secondly, these effects appear not only when the stimulus attribute is task-relevant (for the Simon effect: Umiltà & Nicoletti, 1990; for the SNARC effect: Dehaene, Dupoux, & Mehler, 1990) but also when it is task-irrelevant (for the Simon effect: Lu & Proctor, 1994; for the SNARC effect: Fischer, Warlop, Hill, & Fias, 2004). Thirdly, both effects are assumed to originate from the automatic processing of a positional code (Zorzi et al., 2002; Zorzi & Umiltà, 1995) that primes lateralized responses and interferes with the task-relevant response code. Finally, the SNARC and the Simon effects occur across a variety of responses and interact with the response selection stage of action (For the Simon effect: De Jong, Liang, & Lauber, 1994; Valle-Inclàn, 1996; van der Lubbe, Jaskowski, Wauschkuhn, & Verleger, 2001; for the SNARC effect: Daar & Pratt, 2008; Keus, Jenks, & Schwarz, 2005; Keus & Schwarz, 2005; Wilson & Pratt, 2007). Although the SNARC and the Simon effects share these various characteristics, several studies also showed that they present a different mechanism: while the SNARC is not affected by the speed of response or by the length of the stimulus onset asynchronies (SOA_s) (Daar & Pratt, 2008; Mapelli et al., 2003), the Simon effect only occurs when the speed of response is fast (Mapelli et al., 2003). It could therefore be argued that these two phenomena are spatial in nature but rest on distinct parietal mechanisms (Mapelli et al., 2003; Stoianov, Umiltà, & Zorzi, 2005).

Here, we only highlighted a small difference between the Simon and SNARC results. While the low visuo-spatial children demonstrated the SNARC effect in both hand conditions, the Simon effect of this group only appeared in the crossed posture. While this discrepancy does not find any rationale explanation, it doesn’t contest at all the idea that allocentric coordinates principally guided the behaviour of our both groups.

It is interesting to note that children with low visuo-spatial skills presented the same SNARC effect as those with high visuospatial skills. In the study of Bachot et al. (2005), in contrast, no SNARC effect was found in a group of children suffering from both NVLD and dyscalculia. Although the children tested in our study were not diagnosed as NVLD, this difference in results might suggest that the absence of the SNARC effect is probably more related to the presence of dyscalculia than to the presence of NVLD. However, this interpretation should be directly tested by running the same experiment on children with a NVLD deficit but no concomitant dyscalculia as well as on children with dyscalculia and no NVLD.

Children from the high visuo-spatial group also demonstrated the classic pseudo-neglect effect (Jewell & McCourt, 2000) in the numerical tasks. To our knowledge, our study is the first one to demonstrate the presence of this effect in grade 4 children. High visuo-spatial children indeed tended to underestimate the expected answers of the number bisection and number-to-position tasks. Low visuo-spatial children, in contrast, manifested the pseudo-neglect effect but only in the number-to-position task. As high and low visuo-spatial children showed the typical magnitude effect (in the number bisection and number comparison tasks), a linear mapping between Arabic numbers and space in the number-to-position task and a SNARC effect in the magnitude comparison task, we suggest that both groups could rely on a number magnitude representation that obeys Weber's law and presents the same left-to-right orientation. One limitation of our study should nevertheless be acknowledged. The 0-100 interval was indeed used in the number-to-position task while it is generally assumed that this numerical range is typically mastered in second grade (Siegler & Booth, 2004). The use of larger scale (i.e., 0-1000) could have highlighted group differences, for example a logarithmic scaling in low visuo-spatial children and a linear scaling in high visuo-spatial children. This idea remains to be tested. As the low visuo-spatial group was less accurate than the high group in basic spatial processing (i.e., line bisection), in tasks involving an external spatial medium (i.e., number-to-position) as well as in tasks involving an internal representation of numbers (i.e., number bisection and a tendency for less accurate response in magnitude comparison), our results nevertheless suggest that the accuracy of the mental number line is lower in the low visuo-spatial group than in the high visuo-spatial group.

In the literature, numerical difficulties were highlighted in NVLD children but also in children presenting developmental dyscalculia (DD) (Szűcs & Goswami, 2013). While NVLD are characterized by intact verbal abilities but impaired visuo-spatial skills (Nichelli & Venneri, 1995), DD children present a weakness in mathematics without any discrepancy between their verbal and performance IQs (Mamarella, Bomba, Caviola, Fiorenza, Neri, Lucangeli, & Nacinovich, 2013). Children with NVLD were therefore hypothesized to not have a generalized difficulty with calculation per se. Their problems in mathematics were instead thought to emerge because calculation involves the use of the visuo-spatial working memory (Cornoldi, Rigoni, Tressoldi, & Vio, 1999; Mammarella & Cornoldi, 2005; Mammarella et al., 2010; Venneri et al., 2003). While DD children may present visuo-spatial working memory deficits as well (Szűcs, Devine, Soltesz, Nobes, & Gabriel, 2013), the currently dominant theory of DD is, in contrast, related to the impairment of the approximate number system (Landerl, Bevan, & Butterworth, 2004; Piazza, Facoetti, Trussardi, Berteletti, Conte, Lucangeli, Dehaene, & Zorzi, 2010; Wilson & Dehaene, 2007). Our paper is a first step towards a better understanding of how visuo-spatial problems may cause numerical deficits. However, as no working memory measures were administered to the children, the relationship between visuospatial working memory and the allocentric and egocentric representations of numbers remains to be investigated. It should also be interesting to examine different aspects of calculation to better distinguish NVLD and DD profiles. Moreover, as we only test high and low visuo-spatial children, further studies should also consider populations of children with stronger visuo-spatial deficits (i.e., children suffering from diagnosed non-verbal learning disabilities) and examine the impact of this learning disorder on the development of number magnitude representation.

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Footnotes

[1] Two major theoretical models have been proposed to conceptualize how numerical processing obeys Weber's law: the mental number line model and the accumulator model. In this paper, we only detailed the first model which suggests that numbers are logarithmically represented on a line by equal distributions of activation. However, the accumulator model, which suggests that numerosities are represented by magnitudes on an analogue linear representation with scalar variability (Gallistel & Gelman, 1992, 2000; Whalen, Gallistel and Gelman, 1999), produces similar behavioral expectations.

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