

Number sense in children with visuospatial disabilities: orientation of the mental number line

JAN BACHOT¹, WIM GEVERS², WIM FIAS², HERBERT ROEYERS³

Abstract

Various sources of information demonstrate a tight link between visuospatial and numerical disabilities. In the past, this link has been attributed to the involvement of visuospatial peripheral support systems like for instance visuospatial working memory in numerical cognition. However, it is also possible that the association of visuospatial and numerical abilities has a more basic origin. The basic mental representation of numerical magnitude has been shown to take the form of an oriented mental number line in normally developing children and adults, as evidenced by the SNARC effect (preference for left-hand responses to small numbers and right-hand responses to large numbers). To investigate the possibility of abnormal spatial number coding in children with combined visuospatial and numerical disabilities, we measured the SNARC effect in a visuospatial disability group (VSD) during a number comparison task (smaller or larger than 5) and compared it to a matched control group. A SNARC effect was obtained in the control group but not in the visuospatial disability group. This result is a first indication that the link between visuospatial and numerical disabilities may be mediated by a basic abnormality in representing numerical magnitudes on an oriented mental number line.

Key words: SNARC, visuospatial disability

¹ J. Bachot, Center of Mental Health Andante, Herculustraat 17, B-2600 Antwerp, Belgium; Phone: +32 3-2703773, Fax: +32 3-2703774; E-mail: jan.bachot@andante.be

² Department of Experimental Psychology, Ghent University, Ghent, Belgium

³ Department of Experimental Clinical and Health Psychology, Ghent, Belgium

The relation between visuospatial problems and mathematical disability has been primarily attributed to dysfunctions at the level of peripheral support systems, like working memory, visual imagery (Keeler & Swanson, 2001; Reuhkala, 2001) or visuospatial attention, causing deficiencies in retrieval and/or procedural operations (for review see Geary & Hoard, 2001). In this paper we do not concentrate on these visuospatial functions supporting mental arithmetic, but we focus on the central representation of numerical meaning, being the core component of numerical and mathematical knowledge (Dehaene, 1992; Wynn, 1998), and show that the spatial component of this central representation is affected in children with visuospatial disabilities.

Recent studies show that animals (Nieder, Freedman, & Miller, 2002; Sawamura, Shima, & Tanji, 2002) and human infants (Wynn, 1996) are able to represent numerosity and to discriminate it from other numerosities. The most important variable determining quantification performance is the numerical distance between the numerosities to be discriminated: discriminability increases with increasing difference between the two sets of elements. Put more simply: a set of 2 elements can be more easily discriminated from a set of 4 elements than from a set of 3 elements. Moreover, this distance effect is modulated by numerical size. For larger numerosities, the numerical distance between the to-be-compared sets needs to be larger in order to be discriminable (Xu & Spelke, 2000).

With further development the capacity of the number line representation is extended and its representational accuracy increased (Dehaene, 2001; Verguts & Fias, 2004). Mastery of symbol systems like language, and particularly the number word list and its integration with explicit counting procedures (Gallistel & Gelman, 1992) can be expected to be the primary determinants of the development of the initial representation to a more efficient system. Importantly, when healthy adults compare quantities, be they presented as collections of items (Buckley & Gillman, 1974; Fias, Lammertyn, Reynvoet, Dupout, & Orban, 2003) or as symbols expressed in Arabic digit format (e.g. Moyer & Landauer, 1967) or verbal modality (Dehaene, 1992), numerical distance remains the most important determinant of performance. Even after extensive training the distance effect does not disappear (Dehaene, 1997). This strongly suggests that the representations underlying adult performance originate from the initial representational ability available in early childhood.

Yet, increased capacity and accuracy is not the only development of the number line representation. Recent research shows that the number line representation becomes spatially coded: small numbers are associated with left and large numbers with right. This spatial coding was first demonstrated by Dehaene, Bossini, and Giraux (1993) in normal adults as a Spatial Numerical Association of Response Codes effect: when doing parity judgment with key presses as response, subjects exhibited faster left hand than right hand responses to small numbers, the reverse being true for large numbers. Further research showed that the effect is not specific to parity judgment and is robustly observed in other tasks (e.g. Fias, Brysbaert, Geypens, & d'Ydewalle, 1996; Fias, Lauwereyns, & Lammertyn, 2001). In a developmental study, Berch, Foley, Hill, and Ryan (1999) showed that the SNARC effect in parity judgment emerges from the third grade. However, it should be noted that parity judgment is a task which requires relatively advanced mathematical knowledge. Therefore, the actual spatial coding of magnitude representations may occur at a younger age (Fias & Fischer, 2005), although a critical age has not been determined. It has been hypothesized that the SNARC effect depends on reading habits: Lebanese subjects who are used to read from right to left tend to exhibit an inverse SNARC effect (large-left and small-right; Zebian, in press).

It is hard to tell, though, whether this reversal is a direct consequence of reading direction or from a more general culturally-determined habit of ordering information from right to left (Tversky, Kugelmass, & Winter, 1991).

In sum, the normal core mental representation of numerical magnitude takes the form of an oriented number line, with two behavioral effects emanating from this kind of representation: distance and SNARC effect. The distance effect is present in the initial stages of development whereas the spatial coding of the number line is acquired later.

In this study, we address the question to what extent the spatial coding of the mental number line develops normally in children with visuospatial disabilities, with otherwise normal verbal skills, who showed also problems on arithmetic, next to a much better level on reading. To exclude differences in automaticity from our results, the SNARC effect was measured in the context of a magnitude comparison task, which requires access to the mental number line for correct task performance.

Method

Participants

The sample consists of 32 children in the range from 7 to 12 years. Half of them belonged to the group of children with visuospatial disability (VSD group), the other half was a matched control group. The VSD group consisted of 16 children (mean age = 9,29; SD=1,21), who were referred to a Centre of revalidation or a Mental Health Centre for children and adolescents with complaints of emotional and/or learning disorders. They were called upon post-hoc and were submitted to a series of neuropsychological tasks. They had relatively low scores on Performance IQ compared to normal Verbal IQ of the WISC-R and WISC-III going together with visuospatial disabilities and dyscalculia (see Table 1). They all had low scores on the block design subtest.

They also had difficulties with visuospatial tasks such as the spatial task of the PMA (Thurstone & Thurstone, 1962), the Judgement of Line Orientation (Benton, Hamsher, Varney, & Spreen, 1983), the Developmental Test of Visual Motor Integration (Beery, 1997). They performed the latter in a deficient way without having difficulties on the supplemental developmental tests of Visual Perception and Motor Coordination. Children with problems in motor coordination were excluded from the experimental group. Moreover, we administrated a test for visuo-spatial working memory, the VSS (de Sonneville, 2001). They also did an arithmetic task for complex addition and number concepts (KRT, Cracco, 1993), a task on simple automatized number facts (TTR, De Vos, 1992), probably based on retrieval from rote verbal memory (Dehaene, 1992) and a reading test on words (Brus, One-Minute Test; Brus & Voeten, 1979) and nonsense words (Klepel-pseudo-word test; Van den Bos, Spelberg, Scheepstra, & De Vries, 1994) at their school level. Comparing mean results of the Arithmetic test and those of reading (see Table 1), the discrepancy is obvious.

The control group consisted of 16 children matched by gender and age ($M=9.24$, $SD=1.15$). These children were recruited from local schools on the basis of both the teachers' referrals and the test scores on the WISC-R or WISC-III as a measure of general intelligence (Spreen & Strauss, 1991) and on reading tests. Verbal intelligence was matched to the

Table 1:
Means, SD and F-values of VSD and Control groups⁴ on the variables.

Test ⁵	VSD (n=16) M(sd)	Control (n=16) M(sd)	F (1)
WISC			
VIQ	108.63 (9.28)	106.19 (5.81)	0.79
PIQ	88.56 (10.56)	107.19 (9.21)	28.28**
BP	7.88 (1.74)	10.06 (1.81)	12.13**
Visuospatial tasks (z-score)			
PMA	-0.36 (0.97)	0.66 (0.93)	9.20**
JLO	-0.60 (0.62)	0.66 (0.84)	23.52**
VMI	-0.36 (0.55)	0.68 (0.63)	24.60**
VMIVP	0.41	0.80	1.85
VMIMC	0.33	0.44	0.17
Visuospatial WM (z-score)			
VSS	-1.90 (1.20)	-0.03 (1.04)	22.31**
Arithmetic (z-score)			
KRT	-1.67 (0.98)	-0.04 (0.63)	31.00**
TTR	-0.53 (1.45)	0.56(1.68)	3.82
Reading (z-score)			
Brus	0.04 (1.49)	0.79 (1.20)	2.46
Klepel	0.06 (0.70)	0.17 (0.53)	0.23

* $p < 0.05$, ** $p < 0.01$

VSD group. (see Table 1). In order to be accepted in the control group, a child's performance IQ should not differ from its verbal IQ (maximal difference of 10).

An ANOVA on the standard scores of the two groups revealed a significant difference between the two groups on all the visuospatial and the complex arithmetic tasks but not on the reading tasks, being average for both groups (F-values provided in Table 1).

Procedure

In a number comparison task, subjects had to decide whether a presented Arabic number was larger or smaller than five. Responses were given on an AZERTY keyboard by means of the letters Q (left) and M (right). Subjects were asked to respond as fast and as accurate as possible. In the first block, subjects had to respond to small numbers with the left hand and to large numbers with the right hand. During the second block this response assignment was reversed.

⁴ M age : VSD 9.29 (1.21); control 9.24 (1.15); F(1)=0.02, p=0.89

⁵ BP: Block Design; PMA: Primary Mental Abilities, figure completion; JLO: Judgement of Line Orientation; VMI: Developmental Test of Visual-Motor Integration; VMIVP: VMI Visual Perception; VMI MC: VMI Motor Coordination; VSS: Visuospatial sequencing; KRT: Kortrijkse rekentest; TTR: Tempo test rekenen; Brus: 1 minute reading test; Klepel: reading test with pseudo-verbs.

Arabic numbers ranging from one to nine (except five) were shown at the center of the screen (height: 1.25° ; width: $.57^\circ$). Each target number was preceded by a fixation cross at the center of the screen for 500ms. Immediately following offset, the target number appeared and remained there until response or 7000ms elapsed. After target presentation the screen remained blank for 500 ms; thereafter a new trial was initiated.

Each target number was presented 10 times, leading to a total of 80 target presentations per block. Both blocks were preceded by a training list in which each target number was presented twice. Target numbers were randomized in such manner that the same number could never be repeated.

Data analysis

The data were analyzed using a regression method proposed by Lorch and Myers (1990, Method 3). For each subject, for each number and for each side of response, median reaction time (RT) was calculated. From these median scores, differences in RT (dRT) were calculated for each subject, subtracting left hand responses from right hand responses. For each subject, dRTs are then regressed with number magnitude as predictor variable. A t-test decides whether the regression slope differs significantly from zero. Because a clear prediction is postulated about the direction of the slope (negative correlation between dRT and number magnitude), all tests are one-sided. The distance effect was analysed using the same method. Because the distance effect is independent from response side, the regression was performed on average RT for each number separately. Subsequently, each number was regressed with the distance towards the reference number five as predictor variable (e.g. distance 4 for targets 1 and 9, distance 3 for targets 2 and 8, etc...).

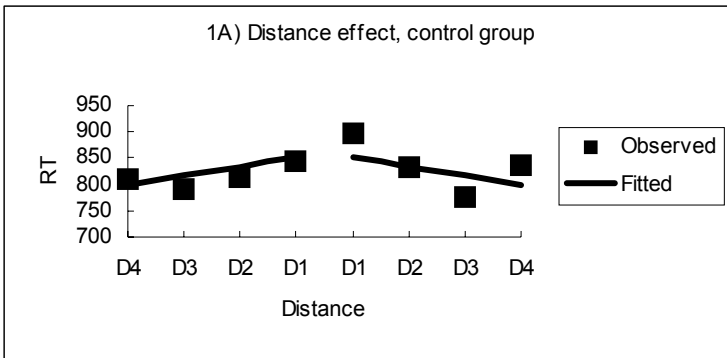
Results

Control subjects

Average error rate over subjects was 4.92% with a maximum of 13.75%. There was no speed-accuracy trade off over the 16 cells of the design ($r = .44$ $n = 16$, $p < .09$), therefore errors were not analyzed separately. Median RT over targets ranging from one to nine was 809, 792, 814, 844, 897, 833, 777 and 835ms, respectively.

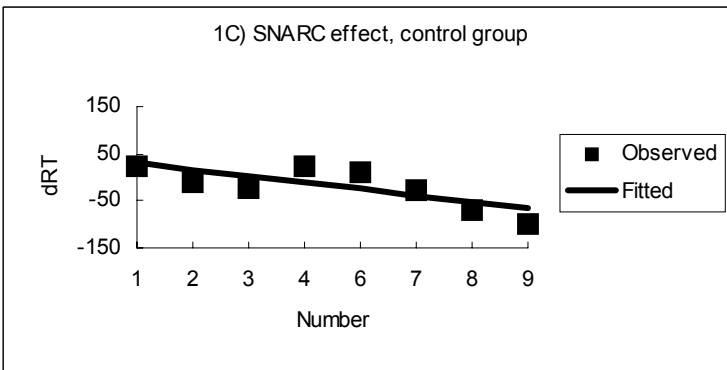
Subsequently, the Lorch and Myers method was applied for revealing possible distance effects. As a result, the following regression equation was obtained:

$$RT = 871.27 - 18.47 (\text{Distance})$$



with distance contributing significantly [$t(15) = -2.03$, $SD = 36.45$, $p < .05$]. Furthermore, the distance effect contributed in a reliable manner up to a distance of 3 from the reference number five [$F(1,15) = 5.63$; $p < .05$]. The analysis to evaluate the presence of a SNARC effect revealed the following equation:

$$dRT = 44.76 - 13.97 (\text{Magnitude})$$



with a significant magnitude slope [$t(15) = -2.12$, $SD = 26.35$, $p < .05$].

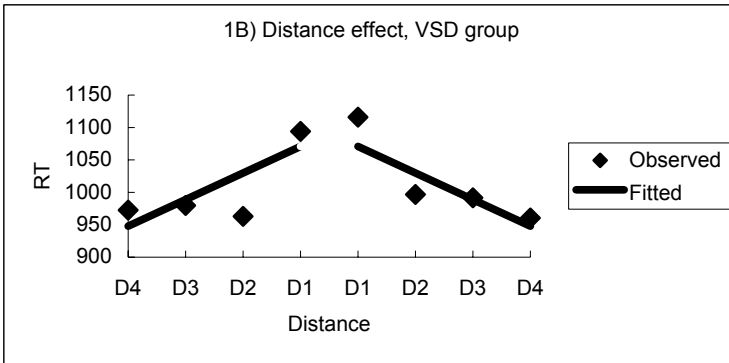
So, both distance and SNARC effects are present when the control subjects performed the number comparison task.

VSD group

Average error rate over subjects was 11.33% (maximal: 31%). A positive correlation over the 16 cells of the design indicated the absence of a speed-accuracy trade-off ($r = .37$, $n = 16$, $p < .2$). Median RT over subjects for each target number ranging from one to nine was

973, 980, 963, 1094, 1116, 997, 992 and 960ms, respectively. The slope value for distance, obtained from the following regression equation differed significantly from zero, $t(15) = -3.82$, $SD = 42.87$, $p < .001$.

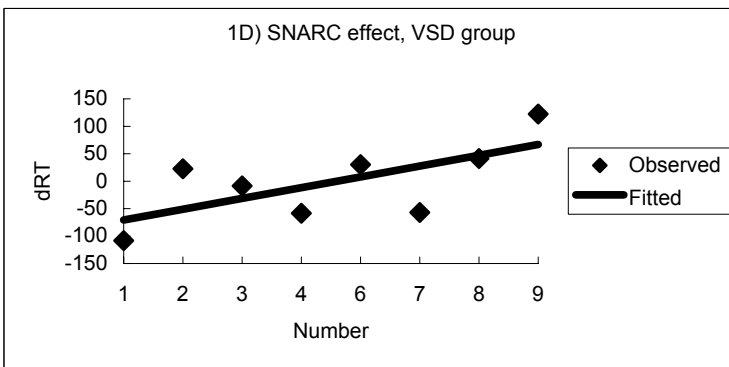
$$RT = 1111.66 - 40.97(\text{Distance})$$



As can be seen in the Figure, there was only a reliable distance effect between distance one and two ($F(1,15) = 5.19$; $p < .05$). The other distances did not reach significance (all $p > .5$).

Finally, the regression analysis was run on the dRTs in order to investigate the SNARC effect. Although Figure 1d shows a positive slope indicative for a reversed SNARC effect, the slope did not significantly differ from zero. $t(15) = 1.35$, $SD = 58.27$, $p > .08$.

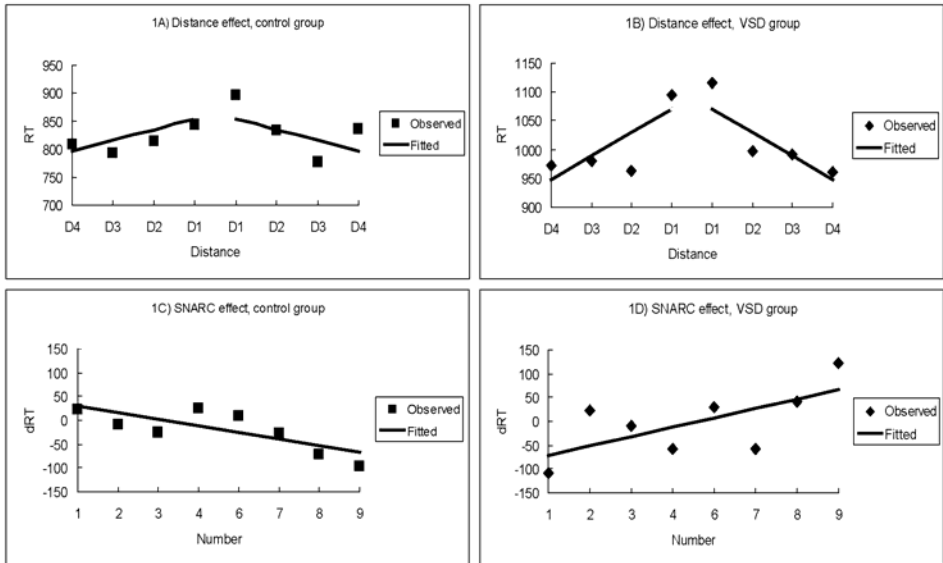
$$dRT = -90.41 + 19.65 (\text{Magnitude})$$



However, in spite of this lack of significance, a significant positive correlation was present between the difference in IQ (VIQ minus PIQ) and the magnitude of the slope ($r = .52$; $p < .05$). Hence, the larger the difference between VIQ and PIQ, the more positive the slope value becomes.

Figure 1:

Upper figures: observed data and regression line representing RT responses as a function of distance by a) the control group and b) the experimental group. Lower figures: observed data and regression line representing RT differences between right-handed minus left-handed responses as a function of magnitude by c) the control group and d) the experimental group.

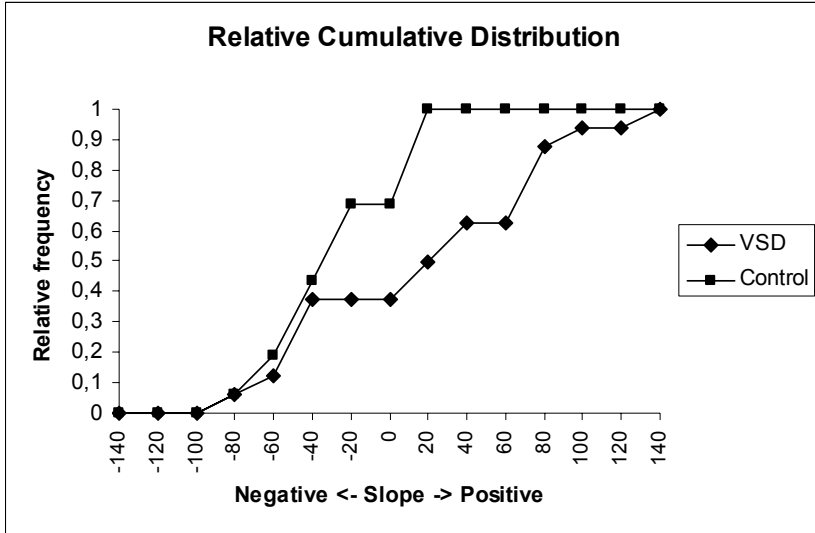


Direct comparison of visuospatial disability and control group

The VSD group was both slower in RT ($t(15) = -2.69; p < .01$) and made more errors ($t(15) = -3.43; p < .01$) than the control group. In order to find out whether the visuospatial disability group and the matched control group were different from each other with regard to the Distance effect and the SNARC effect, dependent sample t-tests on the slopes were performed. For the distance effect, there was a marginal significant difference between both groups, $t(15) = 1.65; SD = 54.48; p < .08$. As can be seen in Figure 1a and 1b the slope reflecting the distance effect is steeper in the experimental than in the control group. Notice also that the distance effect is more fine tuned in the control group than in the experimental group. While the control subjects showed a reliable distance effect up to a distance of three ($F(1,15) = 5.63; MSe = 8793; p < .05$), the VSD group only showed a reliable distance effect when a distance of 1 was compared to a distance of 2 ($F(1,15) = 5.19; MSe = 96583; p < .05$).

Furthermore, the SNARC effect was found to reliably differ between the two groups $t(26) = -2.43, p < .05$. In order to visualize the individual differences in slope in the two groups, figure 2 provides a cumulative frequency distribution of the two groups.

Figure 2:
Cumulative frequency distribution representing both the control and the VSD group as a function of the slope value.



In order to decide whether the values from the VSD group are stochastically more positive than the values of the control group, a Kolmogorov-Smirnov two-sample one-tailed test was applied. The largest difference between both groups was .5 [$D(16,16) = 16 \cdot 16 \cdot .5 = 128$; $p < .05$]. From this analysis it can be concluded that the VSD group shows proportionally more positive values than the control group.

In order to examine the influence of multiple differences and to exclude that the group differences are due to other variables than those of interest we performed the following multiple regression analyses. Group membership appeared to contribute significantly to the slope values for the SNARC effect, $t(30) = -2.10$; $p < .05$ but not for the distance effect $t(30) = 1.60$; $p > .1$. With regard to the SNARC slopes, entering verbal IQ and age into the regression did not alter the results. Neither of these factors predicted the slope values whereas group membership continued to maintain a significant influence $t(28) = -1.91$; $p < .05$ (one-sided).

However, when the scores on each of the visuospatial tasks were taken into consideration, the group difference no longer reached significance, $t(26) = -0.83$, $p > .4$, supporting our conclusion that the missing SNARC slopes in the VSD group rely on deficient spatial processing. When the arithmetic tasks were entered in the regression, the KRT explained most of the variance $t(28) = -1.84$; $p < .08$ whereas the group differences again disappeared, $t(28) = -0.43$; $p > .6$. Whether deficient visuospatial processing is caused by deficient arithmetic processing or the other way round can not be determined on the basis of the present correlational data. Whatever it is, the present data do point to the importance of spatial characteristics in the SNARC effect.

Discussion

In this study, we addressed the question to what extent the spatial coding of the mental number line develops normally in children with visuospatial disabilities, with otherwise normal verbal skills, who also showed problems on arithmetic, next to a much better level on reading. To this end, both the SNARC effect and the distance effect were measured within this VSD group and compared with a control group matched on age and verbal intelligence. A first indication for a difficulty with the mapping of the numbers on an internal number representation was the general finding that performance of the VSD group was both slower and less accurate compared to the control group.

Additionally, it was shown that the control group and the VSD group differ from each other with respect to the SNARC effect. In line with Berch et al. (1999), we found that the control group showed a normal SNARC effect in that small numbers were responded to faster with the left hand and large numbers with the right hand. In contrast, the VSD group showed no evidence for this mapping from magnitude to response side. A number of alternative interpretations regarding the absence of a SNARC effect in the VSD group can be ruled out.

First, it cannot be attributed to the fact that VSD children would have particular difficulties with a change of response assignment halfway the experiment. Because the congruent stimulus-response mapping (small left, large right) was administered first followed by the incongruent mapping, one would then expect an enhancement of the SNARC effect. The fact that the SNARC effect tends to reverse in the VSD group, can have two reasons. One reason could be that the number line of the VSD children is misoriented, i.e. from right to left instead of from left to right. The reverse SNARC effect, albeit non-significant, could also be a reflection of a general training effect because the reversal of the SNARC effect means that the VSD group was faster in the second half of the experiment than in the first half. If this would be the case, this suggests that the VSD children are largely insensitive to the specific S-R mappings. Results from the complementary order of s-r mapping (incongruent followed by congruent) will allow to distinguish between the two interpretations.

A second possible cause for the absence of a SNARC effect is that the VSD group was far too heterogeneous to obtain reliable measures. However, this does not seem plausible because the subjects were carefully selected in order to obtain a homogeneous group. Furthermore, the VSD group was, with the exception of visuospatial properties and arithmetical abilities, matched with a control group that reliably showed the SNARC effect. Moreover, two points of evidence suggest that the positive slope value is not attributable to noise. First, a positive correlation was obtained between the difference in Verbal and Performat IQ (P-V IQ) and the slope value indicating that the larger the P-V IQ, the more positive the slope value becomes. Second, a frequency distribution showed that the VSD group yielded proportionally more positive slope values than did the control group.

This link between visuospatial disabilities and an abnormal representation of numerical magnitudes on an oriented mental number line does not necessarily reflect a direct causal relationship but may be established via an intervening variable. For instance, the specific role of peripheral support systems like working memory needs further investigation. In fact the VSD group performed significantly worse than the control group on a visuospatial working memory task (VSS). From a developmental point of view it seems not contradictory that

deficits in spatial working memory might contribute to a delay or deficiency in building up automatized spatial number representations during early school years.

The finding that the VSD group showed no SNARC effect provides us with first evidence that these children exhibit problems in mapping the numbers on a mental number representation. Converging evidence towards this conclusion were the results obtained for the distance effect. Whereas the control group showed a distance effect, reliable up to a distance of three, the VSD group showed only a reliable distance effect for the numbers 4 and 6.

At this point, the results can only be regarded as a first indication of a problem with the mapping of the numbers on the 'mental number line'. The reason why there is a tendency for a reverse orientation of the mental number line (or the mapping towards the mental number line) remains unclear and cannot be resolved on the basis of the present experiment.

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