Relationships between number and space processing in adults with and without dyscalculia

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Abstract

A large body of evidence indicates clear relationships between number and space processing in healthy and brain-damaged adults, as well as in children. The present paper addressed this issue regarding atypical math development. Adults with a diagnosis of dyscalculia (DYS) during childhood were compared to adults with average or high abilities in mathematics across two bisection tasks. Participants were presented with Arabic number triplets and had to judge either the number magnitude or the spatial location of the middle number relative to the two outer numbers. For the numerical judgment, adults with DYS were slower than both groups of control peers. They were also more strongly affected by the factors related to number magnitude such as the range of the triplets or the distance between the middle number and the real arithmetical mean. By contrast, adults with DYS were as accurate and fast as adults who never experienced math disability when they had to make a spatial judgment. Moreover, number–space congruency affected performance similarly in the three experimental groups. These findings support the hypothesis of a deficit of number magnitude representation in DYS with a relative preservation of some spatial mechanisms in DYS. Results are discussed in terms of direct and indirect number–space interactions.

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1. Introduction

The way human beings represent numbers is partly related to spatial processes. Current research provides indeed clear evidence for a close interconnection between numbers and space (for a review, see Hubbard, Piazza, Pinel, & Dehaene, 2005). According to one of the most popular models, numbers are represented mentally along a mental number line oriented from left to right (Dehaene, 1997). Support for this hypothesis comes from the SNARC effect (i.e., Spatial Numerical Association of Response Codes, Dehaene, Bossini, & Giraux, 1993) which consists of an association between relative number size and response side, such that larger numbers are associated with right side and smaller numbers with left side responses (for a review, see Fias & Fischer, 2005). This effect was initially found in parity judgments when adult participants responded faster to small numbers with the left-hand, and to large numbers with the right-hand (Dehaene et al., 1993; Fias, 2001; Fias, Brysbaert, Gyepens, & d'Ydewalle, 1996). Meanwhile the SNARC was also observed during numerical tasks requiring phoneme monitoring (Fias et al., 1996) or orientation detection (Lammertyn, Fias, & Lauwereyns, 2002). The interactions between numbers and space are confirmed by neuropsychological studies of healthy or brain-damaged adults suffering from left neglect, a disorder of spatial attention impairing awareness of the left side of space following right lesion (for a review, see Halligan, Fink, Marshall, & Vallar, 2003). Contrary to healthy adults who presented a slight leftward bias termed pseudoneglect (Longo & Lourenço, 2007, 2010), these patients showed a bias towards the right not only in physical space, but also when they had to bisect a numerical interval (Priftis, Zorzi, Meneghello, Marenzi, & Umiltà, 2006; Zorzi, Priftis, & Umiltà, 2002). For instance, when asked what number was halfway between 1 and 9, left neglect patients consistently reported a number larger than the expected response, such as 7, shifting the response towards the right end of the mental number line.

Besides the growing body of evidence for a spatial impact on number processing, some studies have explored the number–to-space influence. In an elegant way, Fischer, Castel, Dodd, and Pratt (2003) have demonstrated a shift of visuospatial attention relative to numerical symbol processing. They found that the central presentation of small numbers speeded subsequent detection of peripheral stimuli in the left visual field, while the presentation of larger numbers speeded detection in the right visual field. The use of bisection tasks in combination with numerical material has also provided evidence for the number–space association. When healthy participants had to mark the midpoint of a line consisting of Arabic numerals (Fischer, 2001) or number–words (Calabria & Rossetti, 2005), a bias to the left for small numbers and to the right for larger ones was observed. Such a performance was also seen when flanker
digits were placed to the left and right of physical lines (de Hevia, Girelli, & Vallar, 2006).

While previous findings support interactions between numbers and space in healthy and brain-damaged adults or even in typically developed children (e.g., de Hevia & Spelke, 2009), only few studies have addressed this issue regarding atypical math development. Dyscalculia (DYS) is a pervasive learning disability that is mainly characterised by difficulties affecting the acquisition of basic arithmetic facts (e.g., Barrouillet, Fayol, & Lathuilière, 1997; Garnett & Fleischner, 1983; Geary, 1990), counting (Geary, Hoard, & Hamson, 1999; Landerl, Bevan, & Butterworth, 2004), and the execution of arithmetical procedures (Russell & Ginsburg, 1984). Amongst the several theories which have been proposed to account for math disability, the hypothesis of a spatial deficit has received only little support even if a co-morbidity between visuospatial and mathematical abilities is often observed (Ansari & Karmiloff-Smith, 2002; Simon, Bearded, Mc-Ginn, & Zackai, 2005). Rourke and his collaborator (Rourke, 1993; Rourke & Conway, 1997) postulated that children with DYS only had problems in non-verbal tasks involving visuospatial or psychomotor abilities, while children with better arithmetical than reading scores were impaired in verbal tasks. These results were interpreted as reflecting a left hemisphere dysfunction in children with both mathematical and reading difficulties, while specific problems with mathematics were proposed to stem from a right-hemisphere dysfunction. However, more recent studies failed to find any systematic differences between children with both mathematical and reading disabilities and children with DYS only, except with respect to problem-solving tasks involving verbal comprehension (Hanich, Jordan, Kaplan, & Dick, 2001; Jordan, Hanich, & Kaplan, 2003b). There are however some indications that more basic number processing and spatial mechanisms might be jointly impaired in some populations. Subitizing (Kaufman, Lord, Reese, & Volkmann, 1949), a processing and spatial mechanisms might be jointly impaired in some populations. Subitizing (Kaufman, Lord, Reese, & Volkmann, 1949), a term which reflects the ability to rapidly, accurately, and confidently know the size of small (1–4) visual patterns without counting, was limited to two points in children with DYS (Koontz & Berch, 1996). It was found also that children with both mathematical and visuospatial disabilities did not show the SNARC effect during a number comparison task (Bachot, Gevers, Fias, & Roeyers, 2005). Moreover, when estimating the position of Arabic numbers on physical number lines ranging from 0 to 100, children with DYS were less accurate than children with low mathematical achievement and controls in kindergarten and first grade (Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007). In addition, they did not show the typical shift from logarithmic-based estimations, supposed to depend on the number magnitude representation, to linear-based estimations learned during schooling (Geary, Hoard, Nugent, & Byrd-Craven, 2008). Note that an alternative view assumes that developmental changes in this kind of task reflect an ontogenetic evolution in integrating tens and units into the Arabic place value system (Moeller, Pinxer, Kaufmann, & Nuerk, 2009).

More recently, it was reported that adults with DYS presented difficulties in both physical line and number bisection tasks (Ashkenazi & Henik, 2010). In the physical line bisection, DYS adults presented a small bias to the right while controls showed a large bias to the left due to the asymmetry of attention in the two hemispheres (Jewell & McCourt, 2000). Furthermore, when producing the midpoint of two numbers, DYS adults had a larger leftward bias than controls.

Taken together, these findings support perturbation of spatial processes associated with number comparison or estimation tasks in developmental dyscalculia. However, up to now it is not clear whether the difficulties altering the association between space and numbers originate from a spatial or number magnitude deficit, or from a combined impairment of these processes. Indeed, so far research on dyscalculia focused on the basic inability to represent and manipulate symbolic (Landerl et al., 2004; Mussolin et al., 2010) and non-symbolic (Kaufmann et al., 2009; Piazza et al., 2010) numbers.

Another major problem is the fact that the spatial hypothesis cannot easily be distinguished from an alternative hypothesis postulating a deficit of working memory, particularly the visuospatial sketchpad which serves for holding and manipulating visual and spatial material (Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999). In children, different authors observed a correlation between poor performance in mathematical tasks and a reduced visuospatial span (Bull & Serfis, 2001; Gathercole & Pickering, 2000; McLean & Hitch, 1999). Moreover, Rasmussen and Bisanz (2005) have shown that the visuospatial span measured by Corsi test was the best predictor in performance on non-verbal arithmetic problems for preschool children.

The purpose of the present study is to investigate how numbers and space interact in typical and atypical math development. Adults who exhibited mathematical disabilities during childhood (DYS group) and control adults with average (CON group) or high (MATH group) expertise in mathematics were asked to perform a “numerical landmark test”. Originally, the landmark test was a spatial task requiring the visual comparison of two segments of pre-bisected lines which is used to assess perceptual neglect (Milner, Harvey, Roberts, & Forster, 1993). In the numerical version of the landmark test, three Arabic numbers are presented horizontally and the numerical distances between the two segments defined by the middle and the two outer numbers have to be compared (Nuerk, Geppert, van Herten, & Willmes, 2002). Here we elaborated a modified version of the “landmark task” in which participants had to make one of two possible kinds of judgments, depending on the task instructions. On the one hand, they could be asked to make a numerical judgment and had to decide whether the middle number was the arithmetical mean of the two outer numbers. To do this, they had to compare the numerical distances on both sides of the middle number, ignoring the spatial distances (for instance, by responding that 5 is the arithmetical mean of the two outer numbers in the triplet 2,5,9). On the other hand, they could be required to make a spatial judgment and decide whether the middle number was at the spatial centre of the two outer numbers by comparing the spatial distances on both sides of the middle number, ignoring the numerical distances (for instance by responding that 6 is located at the spatial centre of the two outer numbers in the triplet 2,6,8). In both task versions the relative numerical and spatial distances of the numerals could be (in) congruent with respect to each other. A very similar paradigm was recently used in children, except that only a numerical judgment (i.e., indicate the side where the numerical distance was larger) was required (Lonnemann, Krinzinger, Knops, & Willmes, 2008).

Our modified version of the landmark task allowed us to assess participants’ skills in numerical and spatial judgments and compare the level of three different groups regarding mathematical competencies (DYS, CON and MATH). We also investigated how the congruency between numerical and spatial information influenced participants’ performance in both (numerical and spatial) judgments. In line with current findings, we expect that DYS participants are impaired in numerical judgment. More particularly, we anticipate weaknesses with numerical factors typically influencing performance in number bisection tasks like the range between outer numbers, the distance between the middle number and the real arithmetical mean, multiplicativity and/or interval bisectability (see Method for a description of these effects). Given the role of spatial processing in adults and children with mathematical disabilities, predictions are less clear-cut because up-to-date reports have produced conflicting results. There is indeed no clear indication of a systematic spatial perturbation in performers with low ability in mathematics. We hypothesize that, if spatial mechanisms are relatively preserved in DYS participants, they should be as accurate and fast as controls when judging the spatial location of numbers. Moreover, a similar effect of spatial distances on numerical judgment is expected for all participants. By contrast, if atypical math development is related to
some spatial difficulties, DYS participants should exhibit poorer performance in spatial judgment relative to controls, as well as a lower (or greater) impact of spatial distances on numerical judgments. Finally, another innovative aspect of the present study is to include a group of adults with high expertise in mathematics. With respect to this group, we assume an advantage in numerical judgment compared with CON adults. One could postulate a continuum in performance ranging from MATH over CON to DYS groups suggesting that the same mechanisms are used by all participants but that accuracy and/or speed of processing vary with math abilities. Given the fact that spatial visualisation is closely related to mathematics (Clements, 1983; Fennema, 1975), it is also likely that MATH adults outperform the two other groups in the spatial judgment task.

2. Method

2.1. Participants

A total of 63 volunteer adults with normal or corrected-to-normal vision took part in the experiment. Twenty-two of them have suffered from difficulties in mathematics during development. The remaining 41 participants did not have any learning disability and were assigned to two control groups depending on their mathematical expertise.

2.1.1. DYS group

All adults in this group (17 women and 5 men, mean age = 24.5 years, range = 18–50 years, SD = 6.8) were diagnosed at least once in their past as having dyscalculia. Four of them have presented reading difficulties during the development. The other participants were never diagnosed as having other developmental learning disabilities, such as dyslexia, dysgraphia, or attention deficit/hyperactivity disorder. Some of the DYS participants have received math rehabilitation. However, the majority of them still reported having math difficulties in their everyday life.

2.1.2. CON group

This group was mainly composed by students in psychology or speech therapy (15 women and 5 men, mean age = 21.9 years, range = 17–28, SD = 2.8), and none of them were ever diagnosed as having dyscalculia or any other learning disability.

2.1.3. MATH group

Adults in this group (16 women and 5 men, mean age = 22.5, range = 18–31, SD = 3.7) were students in science with mathematical orientation such as economics, engineering, or architecture. They have not manifested any learning disability during childhood.

2.2. Classification scheme

To confirm the diagnosis of dyscalculia, all participants performed an age-standardized battery of arithmetic tests developed by Shalev et al. (2001) and adapted by Rubinsten and Henik (2005). This battery includes tests assessing performance on arithmetical facts, complex arithmetic problems, decimal numbers, and decimal fractions. Moreover, a timed calculation test was presented to participants who were required to solve addition, subtraction, and multiplication problems on one- or two-digit Arabic numbers. In each task, an arithmetic problem (in 50-point Times New Roman font) appeared at the centre of the screen with two response propositions below. The numerical distance between the correct response and the distracter could be either small (2 for all problems) or large (10 for addition and subtractions problems; from 4 to 9 for multiplication problems). The difficulty was also manipulated by including addition and subtraction problems which required or not report. In multiplication problems, the size of the operands was either small (one-digit number by one-digit number) or large (one-digit number by two-digit number). Twenty problems were presented for each operation in three blocks.

The order of stimuli presentation and the position of the correct response were randomized across trials. Finally, all participants performed a working memory task providing a measure of spatial short-term memory based on the Visual Pattern Test (Della Sala, Gray, Baddeley, & Wilson, 1997). This task consists of the presentation of a series of matrices where half of the cells are filled in black. Participants have to indicate on a blank matrix the locations that were marked in the presentation phase.

The numbers of men and women, mean age, and achievement scores for each group, are given in Table 1. The mean ages did not differ significantly across the three groups (F(2, 60) = 1.62, p > .05), nor did the number of men and women (χ²(2) = 0.18, p > .05). As expected, there were significant group differences on the scores on all arithmetical tests. Regarding the math battery, DYS adults were slower and more error prone than CON and MATH adults. The same pattern appeared for addition, subtraction, and multiplication problems. Although the difficulty and the numerical distance between target and distracter influenced both latencies (F(1, 60) = 83.56, p < .001; F(1, 60) = 78.31, p = .001) and accuracy (F(1, 60) = 8.81, p = .004; F(1, 60) = 19.90, p < .001) of the participants, the impact of these factors was not greater for the DYS group. With respect to the working memory task, we found that the visuospatial span was significantly smaller for DYS adults (7.2) relative to CON (8.4) and MATH (8.4) adults (ps < .05) who did not differ from each other. However, all the three groups were within one standard deviation of the mean of the normative data (9.08 ± 2.25, see Della Sala et al., 1999). At an individual level, only three adults with DYS, and one adult in CON and MATH group performed below these criteria (for all, a score of 6).

Table 1

<table>
<thead>
<tr>
<th></th>
<th>DYS group</th>
<th>CON group</th>
<th>MATH group</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Descriptive information</strong></td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td><strong>Number</strong></td>
<td>N</td>
<td>Gender (M/F)</td>
<td>Age (in year)</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>5/17</td>
<td>24.5</td>
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<tr>
<td></td>
<td>20</td>
<td>5/15</td>
<td>21.9</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>5/16</td>
<td>22.5</td>
</tr>
<tr>
<td><strong>Mathematics</strong></td>
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<td></td>
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<tr>
<td>Math battery (error)</td>
<td>23.7 (12.8)</td>
<td>11.6 (10.7)</td>
<td>4.2 (3.3)</td>
</tr>
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<td>Math battery (RT)</td>
<td>1393 (446)</td>
<td>1057 (227)</td>
<td>945 (352)</td>
</tr>
<tr>
<td>Addition problems (error)</td>
<td>7.7 (1.1)</td>
<td>7.0 (1.1)</td>
<td>3.9 (1.1)</td>
</tr>
<tr>
<td>Addition problems (RT)</td>
<td>4061 (272)</td>
<td>2737 (285)</td>
<td>2842 (279)</td>
</tr>
<tr>
<td>Subtraction problems (error)</td>
<td>13.7 (1.6)</td>
<td>7.8 (1.6)</td>
<td>3.9 (1.6)</td>
</tr>
<tr>
<td>Subtraction problems (RT)</td>
<td>5202 (330)</td>
<td>3526 (346)</td>
<td>3541 (338)</td>
</tr>
<tr>
<td>Multiplication problems (error)</td>
<td>6.0 (0.7)</td>
<td>3.7 (0.7)</td>
<td>2.7 (0.7)</td>
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<tr>
<td>Multiplication problems (RT)</td>
<td>2971 (182)</td>
<td>1903 (191)</td>
<td>1694 (186)</td>
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<tr>
<td><strong>Working memory</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Span supraspan (span)</td>
<td>7.2 (0.8)</td>
<td>8.4 (1.7)</td>
<td>8.4 (1.5)</td>
</tr>
</tbody>
</table>

Note. Standard deviations are shown in parentheses; RTs are given in ms and error in percents. For each category, the frequencies in the same row that do not share subscripts differ at p < .05 (1 tendency at p = .08) regarding the post hoc tests.
processing was analysed in two different ways (see Tables 2A and 16__24__25).

(e.g., 5__8__10) and large distances ranged from 3.5 to 5.5 (e.g., For non-bisectable triplets, small distances ranged from 0.5 to 1.5 mean. For bisectable triplets, small distances were equal to 1 (e.g., distances between the middle number and the actual arithmetical

narrow (from 4 to 8) or wide (from 12 to 18). For

multiplicativity factor was manipulated so that half of the triplets

belonged to a multiplication table (e.g., 6__9__12) and the other half

were preferred to avoid that Simon 3 (e.g., Umiltà & Nicoletti, 1990 ) o r

the first number or closer to the third number or at equal spatial distance from the two outer numbers, yielding the three conditions of congruency: the spatial distance could be congruent (e.g., 5__8_10), incongruent (e.g., 5_8__10) or neutral (e.g., 5_8_10) relative to the numerical distance.

Beside the variables described earlier, “yes” and “no” triplets were controlled for other factors across all conditions such as problem size, average parity, parity homogeneity, and decade crossing (see Appendix A). Finally, 128 triplets were presented in both numerical and spatial tasks across two conditions of congruency, giving a total of 512 stimuli per participant (8 blocks of 64 triplets). To assess a potential general slowdown in DYS participants (Bull & Johnston, 1997), a spatial judgment task on numerically neutral trials, consisting in a block of 24 triplets composed by three identical numbers (e.g., 12__12__12 vs. 12_12___12), was also performed by all participants.

The experiment was displayed on a PC running E-Prime software, version 1.2. (Schneider, Eschmann, & Zuccolotto, 2002). Participants were seated about 50 cm from the computer screen. Each trial started with a fixation rectangle (in which the number triplets occurred) flashed for 100 ms, followed by a grey screen for the same duration. Then, a triplet appeared and remained on the screen until the participant responded via a manual two-key button. In each group, half of the participants were instructed to press the key on the top with their left index when the middle number was the real arithmetical (or spatial) middle, and the key on the bottom with their right index when it was not the case. Top-bottom responses were preferred to avoid that Simon 3 (e.g., Umlitá & Nicoletti, 1990) or SNARC effects interfere with the spatial location of the numbers within the triplet. The assignment of the manual responses was reversed for the other half of the participants. Numbers were presented in Times New Roman font (0.4 or 1 cm wide; 0.6 cm height) and the stimuli were displayed in black on a grey background. Eight blocks of 64 stimuli were presented (4 blocks by task). Trial order was pseudo-randomized so that each stimulus condition appeared about equally often in each block. A supplementary block of 24 neutral triplets was added in the spatial task. For each block, the middle number was at the centre of the two outer numbers regarding the spatial location in half of the trials but not in the other half. The spatial distance between the middle number and the first/third number was manipulated leading to the three conditions of congruency. The inter-stimulus interval was 500 ms and the participant had a few

2 While Nuerk et al. (2002) referred to bisectable and non-bisectable for the same triplets, we labeled them “yes” and “no” triplets to avoid confusion with bisection possibility.
minutes' rest between blocks. The order of tasks was counterbalanced across participants. In each group, half of the adults started with the numerical judgment task and performed then the spatial one, the reverse order was applied to the other half. The experiment was preceded by ten practice trials.

3. Results

A preliminary analysis on neutral triplets showed that median RTs (for correct trials only) in DYS (708 ms), CON (626 ms), and MATH (618 ms) groups did not differ significantly from each other (all, ps > .1). This factor was therefore not included in the subsequent analyses. Since different variables were manipulated for "yes" and "no" triplets, a series of repeated measures analyses of variance (ANOVA) was conducted separately for each kind of items. As this study focuses on number and space processing in typical and atypical math development, only data relative to main effects and interactions with group are reported (see Appendix A for other results). Type of judgment (numerical vs. spatial) did interact with some (but not all) main effects. For simplicity, we have thus chosen to describe these interactions separately for each kind of judgment. Finally, the assumption of homogeneous variances was met for both numerical and spatial judgments in the three groups of participants (all Levene’s tests, ps > .05).

3.1. "Yes" triplets

3.1.1. Error analysis

The error rates were entered in a repeated measures ANOVA with type of judgment (numerical vs. spatial), range (narrow vs. wide), multiplicativity (multiple vs. non-multiple), and conditions of decisional congruency (congruent vs. incongruent) as within-subject factors and order of tasks (numerical-spatial vs. spatial-numerical) and group (DYS, CON, or MATH) as between-subjects factors. In none of the analyses was the order of tasks significant, and neither did it enter into any significant interactions (all ps > .05). The data were therefore collapsed over this factor in a 2 x 2 x 2 x 3 ANOVA.

All main effects except the multiplicativity (F < 1) had a significant impact on error rates. The type of judgment (F(2, 60) = 27.55, η² = .31, p < .001), range (F(1, 60) = 43.01, η² = .42, p < .001), congruency (F(1, 60) = 4.42, η² = .07, p = .04), and group (F(2, 60) = 17.05, η² = .36, p < .001) were significant. Spatial judgments (4.8%) yielded lower error rates than numerical ones (6.8%). Triplets with narrow range (4.9%) were better responded than triplets with wide range (8.4%). The error rate was more important in incongruent trials (7.2%) relative to congruent ones (6.1%). DYS participants (10.1%) were more error prone than CON (6.5%, p = .01) and MATH participants (3.4%, p < .001), the two control groups differing significantly from each other (p = .03).

The type of judgment did interact with the group (Judgment × Group interaction: F(2, 60) = 4.40, η² = .13, p = .017), as well as the multiplicativity (Judgment × Multiplicativity × Group interaction: F(2, 60) = 3.12, η² = .09, p = .05) and the range (Judgment × Range × Group interaction: F(2, 60) = 3.86, η² = .11, p = .026). To understand these interactions, we conducted separate analyses for each kind of judgment. In numerical judgment, a main effect of group (F(2, 60) = 15.65, η² = .34, p < .001) indicated that DYS group (13.3%) committed more errors than CON (8.2%, p < .01) and MATH (4.1%, p < .001) groups that differed marginally from each other (p = .05). The multiplicativity influenced DYS adults (F(1, 21) = 8.77, η² = .29, p = .007) but not CON (F(1, 19) = 2.86, η² = .13, p = .05) and MATH (F < 1) adults. In the DYS group, the triplets that were part of a multiplication table (11.4%) yielded smaller error rates than triplets that did not belong to a multiplication table (15.3%). Finally, the effect of range was highly significant (F(1, 60) = 46.50, η² = .44, p < .001) and was stronger for the DYS group (F(1, 21) = 21.99, η² = .51, p < .001; 18.4% vs. 8.3% for wide and narrow range respectively) relative to CON (F(1, 19) = 12.52, η² = .40, p = .002; 10.8% vs. 5.6%) and MATH (F(1, 20) = 20.29, η² = .50, p < .001; 5.9% vs. 2.3%). In spatial judgment, the group effect (F(2, 60) = 6.02, η² = .17, p = .004) corresponded to a higher error rate for the DYS group (6.8%) than MATH group (2.7%, p < .003) but not than the CON group (4.8%) that did not differ significantly from the two other groups (p > .05). As in numerical judgment, an effect of multiplicativity appeared only in DYS group (F(1, 21) = 6.38, η² = .23, p = .02; CON and MATH: F < 1), but the reverse pattern appeared with more errors for multiplicatively related (7.5%) than unrelated (6.1%) triplets. By contrast, no effect of range was found (F(1, 60) = 1.64, η² = .03, p > .05).

3.1.2. RT analysis

Correct median RTs were submitted to a five-way repeated measures ANOVA (with the same factors as those in the previous analysis). Once again, neither the order of tasks nor interactions with this factor were significant (all, ps > .05). There is no indication of a speed-accuracy-trade-off as revealed by (significant or not) positive correlations between RTs and error rates over the 32 cells of the design.

Only the effect of congruency failed to reach significance (F(1, 60) = 1.2, η² = .02, p > .05). The main effects of judgment (F(1, 60) = 222.88, η² = .79, p < .001), range (F(1, 60) = 136.92, η² = .69, p < .001), multiplicativity (F(1, 60) = 19.75, η² = .25, p < .001) and group (F(2, 60) = 5.71, η² = .16, p = .005) were highly significant. Spatial judgments (664 ms) were faster than numerical ones (3356 ms). Latencies were slower for triplets with wide range (2474 ms) than for triplets with narrow range (1546 ms). Triplets that were part of a multiplication table (1942 ms) yielded faster reaction times than triplets did not (2078 ms). Overall, MATH (1775 ms) and CON (1793 ms) groups were faster than DYS group (2461 ms, all ps < .05).

Besides the main effects, we found a significant interaction between the type of judgment and group (F(2, 60) = 5.32, η² = .15, p = .007) as well as a marginal interaction between the type of judgment and congruency (F(1, 60) = 3.23, η² = .05, p = .077). In numerical judgment, the group effect was significant (F(2, 60) = 5.55, η² = .16, p = .006) showing that DYS participants (4218 ms) were significantly slower than CON (2945 ms) and MATH (2905 ms) peers (all, ps < .05). The two control groups did not differ from each other (p > .05). As depicted in Fig. 1, congruent trials tended to be faster than incongruent trials (3324 and 3388 ms) in the numerical task (F(1, 60) = 2.16, η² = .03, p < .09). In spatial judgment, the latencies were similar in the three groups (705 ms, 645 ms, and 642 ms, respectively for DYS, MATH, and CON groups) as indicated by the lack of group effect (F(2,
effect was reported in the DYS and MATH groups. (small distance: 4.53%; large distance: 6.17%), whereas no distance observed the distance to the middle number and the real arithmetical mean judgments were comparable for the DYS, CON and MATH as the between-subjects factor. All main effects were significant, except judgment and congruency (all, Fs<1). Bisection possibility influenced significantly participants' accuracy (F(1, 60) = 10.26, η² = .15, p = .002) as the bisectable triplets (5.65%) yielded more errors than non-bisectable triplets (4.40%). The distance to the middle (F(1, 60) = 11.88, η² = .16, p = .001) indicated that the error rates were higher in triplets with a small distance (5.65%) relative to triplets with a large distance (4.15%). The effect of group (F(2, 60) = 8.18, η² = .21, p = .001) revealed that DYS adults (7.55%) were more error prone than both CON (5.10%) and MATH (2.44%) adults. Post-hoc t-test showed that DYS group differed significantly from MATH group (p<.001) but not from CON group (p>.05).

More importantly, the lack of Judgment×Group interaction (F<1) showed that the error patterns of the numerical and the spatial judgments were comparable for the DYS, CON and MATH groups. Finally, the Judgment×Distance×Group interaction (F(2, 60) = 3.49, η² = .10, p = .037) indicated that the distance modulated judgment performance differentially in the three populations. In numerical judgment, the effect of distance influenced all groups (DYS group: F(1, 21) = 14.43, η² = .41, p = .001; CON group: F(1, 19) = 6.66, η² = .26, p = .018; and MATH group: F(1, 20) = 13.31, η² = .40, p = .002). As illustrated in Fig. 2, this effect was stronger for the DYS group (11.36% and 4.97% for small and large distance respectively) than for CON (7.11% and 2.58%) and MATH (3.57% and 1.19%) groups. In spatial judgment, the results were somewhat unexpected, because we observed a reversed effect of distance in the CON group only (F(1, 19) = 4.51, η² = .19, p = .047). Indeed, the error rates increased with the distance to the middle number and the real arithmetical mean (small distance: 4.53%; large distance: 6.17%), whereas no distance effect was reported in the DYS and MATH groups.

3.2. “No” triplets

3.2.1. Error analysis

The error rates for “no” items were entered in a repeated measures ANOVA with type of judgment (numerical vs. spatial), bisection possibility (bisectable vs. non-bisectable), distance to the middle (small vs. large) and conditions of decisional congruency (congruent vs. incongruent) as within-subject factors and group (DYS, CON, or MATH) as the between-subjects factor.

As for “yes” triplets, we found significant Judgment×Group (F(2, 60) = 5.64, η² = .18, p = .003) and Judgment×Distance×Group (F(2, 60) = 4.28, η² = .12, p = .018) interactions. Once again, the effect of distance influenced numerical judgment (F(2, 60) = 131.01, η² = .69, p<.001) and was stronger for the DYS group (F(1, 21) = 48.50, η² = .70, p<.001, 3856 ms and 2499 ms for small and large distance) relative to CON (F(1, 19) = 42.73, η² = .69, p<.001; 2964 ms and 1910 ms) and MATH (F(1, 20) = 52.16, η² = .72, p<.001; 2772 ms and 1886 ms) groups (see Fig. 2). Nor group (F(2, 60) = 1.89, η² = .06, p = .05; 710 ms, 640 ms, and 650 ms) neither distance (F<1) effects affected spatial judgment.

However, contrary to “yes” triplets, the congruency effect was not significant and did not interact with group (all, Fs<1), suggesting a similar lack of interaction between numerical and spatial decisions across the three groups for “no” items (but see following result section).

To sum up, both data from “yes” and “no” triplets indicate that the three groups differed with respect to their performance in numerical, but not in spatial judgment. Guttman’s coefficient shows that the items in spatial judgment had very good reliability and internal consistency, providing further pieces of evidence that the lack of group difference was not due to large variability. The split half correlation was .91 for accuracy and .98 for speed of processing. Compared with control peers, DYS participants appeared to be particularly sensitive to psychophysical effects depending on the number magnitude representation (i.e., range, numerical distance to the middle). Other numerical factors (i.e., multiplicativity, bisection possibility) also affected performance of the DYS group. Moreover, congruency between numerical and spatial decisions influenced only performance in “yes” triplets. It was mainly present in the numerical

![Fig. 1. Mean of median RTs (on the left panel) and of error rates (on the right panel) for “yes” items relative to decisional congruity condition in both numerical and spatial tasks across the three groups.](image-url)
3.3. Representational congruency analyses (for “no” triplets only)

In the previous analyses, the congruency effect was examined regarding the relationship between the decision concerning the spatial and the numerical middle (i.e., “decisional” congruency). Another way to consider congruency is to explore the relative positions of the numbers on the spatial continuum and the (mental) number representation. Recoding the triplets according to their “representational” congruency yielded new congruent, neutral, and incongruent conditions for the “no” triplets, whereas it resulted in the same congruent and incongruent conditions than for space-number congruency at the decisional level (see Table 2B). Error rates and corrected median RTs for “no” triplets were entered in a repeated measures ANOVA with type of judgment (numerical vs. spatial), new conditions of representational congruency (congruent, neutral, or incongruent), and numerical distance (small vs. large) as within-subject factors and group (DYS, CON, or MATH)\(^4\) as the between-subjects factor.

3.3.1. Error analysis

Once again, the distance (\(F(1, 57) = 7.94, \eta^2 = .12, p = .007\); 5.7% and 4.1% for small and large distance respectively) and the group (\(F(2, 57) = 8.13, \eta^2 = .22, p = .01\); 7.6% and 4.9%, and 2.3% for DYS, CON, and MATH groups) were significant. By contrast, the type of judgment was not significant (\(F = 1\)). More importantly, we found a Distance × Congruency × Group interaction (\(F(4, 114) = 109.48, \eta^2 = .10\); \(p = .01\)) indicating that the distance effect differed in the three groups. Indeed, the main effect of distance approached significance in DYS (\(F(1, 21) = 4.3, \eta^2 = .17, p = .05\); 8.8% and 6.4%) and MATH (\(F(1, 18) = 3.8, \eta^2 = .17, p = .06\); 2.8% and 1.8%) groups irrespective of congruency conditions (no Distance × Congruency interaction in DYS group: \(F(2, 42) = 2.3, \eta^2 = .10, p > .05\); and MATH group: \(F = 1\)). In the CON group, the effect of distance was significant only in neutral trials (neutral: \(F(1, 18) = 5.51, \eta^2 = .23, p = .03\); 6.7% and 3.8% for small and large distances; incongruent: \(F(1, 18) = 3.19, \eta^2 = .15, p = .09\); 5.9% and 3.1%; congruent: \(F(1, 18) = 1.21, \eta^2 = .06, p > .05\); 4.1% and 5.8%), as revealed by a Distance × Congruency interaction (\(F(2, 36) = 4.2, \eta^2 = .19, p = .02\)).

3.3.2. RT analysis

As reported before, the main effect of judgment (\(F(1, 57) = 291.58, \eta^2 = .84, p < .001\)), distance (\(F(1, 57) = 90.83, \eta^2 = .61, p < .001\)), and group (\(F(2, 57) = 5.21, \eta^2 = .15, p = .008\)), as well as the interaction between these three factors (\(F(2, 57) = 3.1, \eta^2 = .10, p < .05\)) influenced performance on “no” triplets. Furthermore, two new results were provided by this analysis. First, the congruency effect was also significant (\(F(2, 114) = 12.34, \eta^2 = .18, p < .001\)) but in numerical judgment only (Congruency × Judgment interaction: \(F(2, 114) = 11.37, \eta^2 = .17, p < .001\)), indicating that congruent trials (1542 ms) were faster than both neutral (1616 ms, \(p = .01\)) and incongruent (1697 ms, \(p < .001\)) ones which differed marginally from each other (\(p = .07\)). This “representational” congruency effect did not interact with group (\(F(4, 114) = 1.14, \eta^2 = .04, p > .05\), suggesting that DYS, CON and MATH adults were similarly influenced by the congruency between the numerical and spatial distances (see Fig. 3). Second, a Judgment × Distance × Congruency interaction was highly reliable (\(F(2, 114) = 25.47, \eta^2 = .31, p < .001\)). Separate analyses by kind of judgments revealed that the effect of distance differently influenced the three congruency conditions. In numerical judgment, a typical distance effect – i.e., faster RTs for large numerical distance relative to small numerical distance – was found in all conditions of congruency (congruent: \(F(1, 57) = 24.95, \eta^2 = .30, p < .001\); neutral: \(F(1, 57) = 133.58, \eta^2 = .70, p < .001\); incongruent: \(F(1, 57) = 98.63, \eta^2 = .63, p < .001\)). In spatial judgment, a similar pattern appeared for incongruent trials (\(F(1, 57) = 4.9, \eta^2 = .08, p < .05\); 681 ms and 656 ms for small and large numerical distance respectively) whereas the distance effect was absent for neutral trials (\(F = 1\); 670 ms and 663 ms) and reverse for congruent ones (\(F(1, 57) = 7.07, \eta^2 = .11, p = .01\); 652 ms and 672 ms).

To sum up, not only “decisional” congruency but also “representational” congruency between numerical and spatial information had an impact on the numerical judgment. Moreover, we found that the irrelevant numerical distance between numbers affected the spatial judgment. Crucially, these patterns of results were observed in the three groups of participants, supporting the view that bidirectional influences between number and spatial processing exist in both control and mathematically disabled adults.

\(^4\) Due to problems with the computer hardware, we were not able to compute median RTs related to these new conditions for three participants (one in CON group and two in MATH group).
4. Discussion

The aim of the present study was to analyse interactions between number and space processing in adults with or without dyscalculia using a new version of the landmark test. In the following, we first present our findings concerning the numerical and the spatial landmark tests, as well as the interrelations between them with respect to typical math development (CON group). In a second step, we then examine differences between DYS and control participants relative to number and space processing. Third, we tentatively investigate whether performance in MATH group differs from CON ones.

Regarding numerical judgment, performance was found to be mediated by number magnitude but also by other numerical variables such as multiplication fact knowledge stored in long-term memory and implicit use of parity information (Nuerk et al., 2002; Wood et al., 2006). Generally we found similar effects as those reported in previous studies using the number bisection task (Nuerk et al., 2002). For “yes” items, our participants were faster and more accurate in responding to triplets covering a narrow range than to triplets covering a wide range. Moreover, latencies were speeded up for triplets that belonged to a multiplication table relative to other triplets. For “no” items, the distance to the middle affected both speed and accuracy of participants, as reflected by an easier rejection for triplets with a middle number far away from the real arithmetical mean. Similarly, non-bisectable triplets (whose two outer numbers did not share the same parity) were rejected faster and more accurately than bisectable triplets.

Assessing in parallel performance in spatial judgment on the same set of triplets enabled us to examine interactions between numerical and spatial judgments. As already mentioned, a space-to-number influence was reported by numerous recent studies investigating for instance the SNARC effect in adults (Fias & Fischer, 2005), or number line bisection tasks in healthy controls (Calabria & Rossetti, 2005; Fischer, 2001) and neglect patients (e.g., Zorzi, Priftis, Meneghello, Marenzi, & Umlità, 2006). In the present paper, the congruency between the spatial location of the middle number and its magnitude affected participants’ performance on “yes” items. The acceptance of the middle number as the real arithmetical mean of the two outer numbers was easier when this number was also at the spatial centre of the two outer numbers than when this was not the case. This was reflected by higher error rates for incongruent than congruent triplets in both spatial and numerical tasks, and by faster latencies for congruent relative to incongruent triplets in numerical judgment only. The response pattern was slightly different for “no” items. Indeed, the fact that the middle number was (or not) situated at the spatial centre within the triplet did not influence its rejection as the non-arithmetical mean of the two outer numbers. However, this did not mean that the spatial location of the middle number had no impact on numerical judgment in “no” items. With respect to “representational” congruency, responses were faster when the magnitude of the middle number was congruent with the spatial distance between it and the two outer numbers (e.g., 3...6...8) than when number magnitude and spatial distance were neutral (e.g., 3...6...8) or incongruent (e.g., 3...6...8). This effect mainly appeared when the middle number was close to the arithmetical mean. It should be noted that the reverse was observed by Lonnemann et al. (2008) in children, as a congruency effect was found only for triplets with large numerical distance. A plausible explanation is that children had very high error rates for triplets with small numerical distance (40-50%), preventing any congruency effect on latencies. Alternatively, it may be that adults have developed an estimation strategy to rapidly reject the middle number when it was far from the arithmetical mean, whereas children as young as 8–9 years of age might not yet be able to use this kind of strategy, allowing the spatial information to influence the numerical judgment.

Besides the impact of spatial factors on numerical judgment, we also found some evidence for an impact of numerical factors on spatial judgment. The number-to-space influence was first demonstrated by Fischer and colleagues using a detection paradigm (2003; see also Galfano, Rusconi, & Umiltà, 2006; Ristic, Wrigh, & Kingstone, 2006). Other support comes from investigations on physical line bisection flanked by a number to the left or right (de Hevia et al., 2006). Such an impact was reflected here by the effect of numerical distance on spatial judgment. Although this factor was irrelevant for the spatial judgment, the numerical distance between the middle number and the real arithmetical mean of the two outer numbers influenced performance on “no” triplets in the spatial task. Regarding incongruent trials, a typical effect of numerical distance was observed. It was easier to reject the middle number as the spatial centre when it was numerically far from the arithmetical mean (e.g., 21...26...27) than when it was closer (e.g., 21...25...27). The reverse pattern appeared in congruent trials – i.e., triplets whose middle number was numerically close to the arithmetical mean (e.g., 21...25...27) were more easily rejected than triplets whose middle number was more distant (e.g., 21...26...27). One possible explanation for this result is that the spatial arrangement of the three numbers in the triplet automatically activates our mental representation of numbers which is supposed to be logarithmic (Dehaene, Izard, Speike, & Pica, 2008; but see Gallistel & Gelman, 1992 for an alternative view). Consequently, participants might spontaneously be inclined to respond “yes” to indicate the match between spatial and numerical representations. For the “no” triplets in the spatial task, this would then lead to a greater difficulty to accept the (incongruent) spatial decision (e.g., 21...26...27). In contrast, the same automatic process would yield response facilitation when the locations of numbers in the “no” triplets do not respect the mental number line (e.g., 21...26...27). A similar interpretation could account for the effect of multiplicity in DYS participants (see following discussion).

In a great majority of studies using Stroop-like paradigms, the impact of irrelevant numerical information on physical dimensions is restricted to a congruency effect. Indeed, the magnitude (i.e., cardinal value) of Arabic numerals facilitates or interferes with the processing of physical size (e.g., Tzelgov, Meyer, & Henik, 1992), height (Rubinseten & Henik, 2005), or luminosity (Pinel, Piazza, Le Bihan, & Dehaene, 2004). An implicit effect of numerical distance, as reported here, is more rarely observed (see Girelli, Lucangeli, & Butterworth, 2000 for a reverse numerical distance effect in physical judgments). One interpretation is that the congruency and numerical distance effects represent two (progressive) different steps of number magnitude activation. Tzelgov et al. (1992) argue that numerical distance effect results from an algorithmic mechanism and should influence performance only in relevant numerical judgment, while the congruency effect should influence both irrelevant and relevant numerical judgments through a memory-based mechanism. Our data challenge this view by showing that the numerical distance influenced the spatial judgment whereas the congruency did not. Rather, we suggest that the presence (or absence) of these two effects strongly depends on task demands. Compared with numerical Stroop paradigms that require comparing two Arabic numerals varying in physical and numerical sizes, the “numerical” landmark test presents at least two main differences. First, our participants had to process three numbers aligned horizontally according to their magnitudes. It may be that this particular spatial disposition elicits a numerical interference in terms of number representation rather than in terms of magnitude competition. Second, in our spatial task, the potential interference of numerical decision is conditioned by the computation of the mean of the two outer numbers. Considering that the numerical judgment was four times slower than the spatial one, it may be that such a mechanism might be initiated but not completed in time to interfere with the spatial decision (Mussolin & Noël, 2007). Following this assumption, information related to numerical decision (but not
information related to numerical representation) could thus not be automatic enough to interfere with spatial processing. A similar conclusion was reached by a study reporting facilitation/interference effects of the length judgments on numerosity but not the reverse (Dormal & Pesenti, 2007).

A second goal of the present study was to provide more information about differences between DYS and control participants relative to number and space processing. The current data corroborate previous findings that dyscalculia could be associated with a basic impairment of the ability to manipulate numbers explicitly (Wilson & Dehaene, 2007) which is persistent throughout the development (Shalev, Manor, & Gross-Tsur, 2005). Adults with DYS were slower than both CON and MATH in judging the magnitude of Arabic numbers irrespective of whether they had to reject or accept the middle number as the real arithmetical mean of the two outer numbers. Moreover, the deficit of DYS group was not restricted to a generic slowdown in number processing, but had also an impact on the typical effects observed in number bisection tasks and which depend on the number magnitude representation. Compared with control peers, DYS participants showed greater difficulties to accept triplets covering a large range. In a same way, a close distance between the middle number and the arithmetical mean strongly influenced both error rates and latencies especially in adults with DYS. This is consistent with a recent report of a greater impact of numerical distance on number comparisons in children with DYS (Mussolin, Mejias, & Noël, 2010). The present results are also in line with neuroimaging data showing atypical brain activation in DYS participants in regions dedicated to number processing (Kaufmann et al., 2009; Mussolin, De Volder, et al., 2010). Taken together, our findings support the hypothesis that the representation of number magnitude is fuzzier in math disability than in healthy control populations. However, this number magnitude representation could be sufficiently preserved to induce numerical interference. This interpretation could explain why we and others (Rouselle & Noël, 2007) reported that DYS and control participants were similarly influenced by the irrelevant information related to number magnitude. Finally, the impairment of DYS participants was not restricted to number magnitude related factors. Compared with controls, they were more strongly affected by the multiplicativity in both numerical and spatial judgments. When making numerical decision, DYS participants had greater difficulties to accept triplets that were not part to a multiplication table. When judging the spatial location of numbers, they were more error prone for triplets that belonged to a multiplication table. We have no clear explanation for this result. Together, these findings could be interpreted as an automatic retrieval of the triplets that were part of multiplication tables in DYS adults. However, this proposal is at odds with the amount of research showing persistent difficulties in learning and remembering basic arithmetic facts in DYS children (e.g., Barrouillet et al., 1997; Garnett & Fleischner, 1983; Geary, 1993; Mussolin & Noël, 2008). Moreover, the same trend appeared in CON adults but not significantly probably due to low error rates. Rather, the impact of multiplicativity might reflect the use of different strategies depending on the group. It is very likely that CON adults rely on a system of representation based on number sense (Dehaene, 1997) to perform our numerical and spatial judgment tasks. By contrast, this system being impaired in dyscalculia, a verbal strategy could be used by DYS adults resulting in a greater implication of factors based on rote verbal processes such as multiplicative facts.

Our data indicated that DYS participants showed poorer performance than both CON and MATH groups when they had to explicitly judge the magnitude of the numbers. On the contrary, no clear differences between DYS and control peers were found when they had to judge the spatial location of the same numbers. This important finding suggests that at least some visuospatial mechanisms are intact in the context of math disability. Adults with DYS were able to estimate the location of numbers as accurately and quickly as adults who never manifested difficulties in math during the development. This information also automatically influenced their numerical judgments, as demonstrated by the typical congruency effect. ‘Space’ is a broad concept that covers an amount of different cognitive functions (Halpern, 2000; Kimura, 2000). Although a large body of evidence reveals interactions between numerical and spatial mechanisms, other data point towards dissociations between some of them. Doricchi and colleagues (Doricchi, Guariglia, Gasparini, & Tomaiuolo, 2005) compared number interval bisection and physical line bisection in two groups of left neglect patients. Patients with complete hemianopia showed a strong rightward/leftward deviation with longer/smaller intervals in physical line bisection. By contrast, estimation in number interval bisection was within normal range. In patients without hemianopia, a rightward deviation was present with large number intervals, but no clear deviation was found in physical line bisection. In the same vein, Rossetti et al. (2004) reported that two patients with partial or no hemianopia following a frontotemporalparietal ischemia exhibited a mild leftward shift on physical line bisection and a reliable rightward shift on number bisection. A similar dissociation between performance in physical line bisection and number bisection tasks was recently reported in healthy participants (Doricchi et al., 2009). These results suggest that mechanisms requiring estimation of number intervals are at least partly different from those recruited by estimation along spatial dimensions (for a computational modeling of dissociations between numerical and spatial deficits, see Chen & Verguts, 2010). However, these specific findings do not preclude that spatial deficits could exist in math disability (Ashkenazi & Henik, 2010). Even if their performance on visuospatial working memory task was within normal range, our DYS participants had a smaller span than control adults. Such a visuospatial weakness might account for some numerical difficulties of children in arithmetic (Rasmussen & Bisanz, 2005) or in more basic number processing (Bachot et al., 2005; Koontz & Berch, 1996). The literature is only beginning to address the important question of how space and numbers interact regarding atypical math development. Further investigation is required to disentangle spatial processes which are independent from number processing, and spatial processes which are directly linked to the number magnitude representation.

Finally, the inclusion of adults with high expertise in mathematics allowed us to investigate potential advantages compared with adults with moderate expertise. We found only a slight facilitation for number and spatial processing in the former group. MATH adults committed fewer errors than CON adults in both numerical and spatial judgments, although no difference appeared regarding latencies. It is very likely that our version of landmark test implies basic numerical processes which are not sufficiently demanding to point out stronger differences between proficient and highly proficient adults.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.actpsy.2011.06.004.

References


