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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.

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, Geypens, & 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 & Lourenco, 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

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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, & Lathulière, 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, Bearden, 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 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, Pixner, 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 & Scerif, 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___8). 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