Correspondences

Impaired parietal magnitude processing in developmental dyscalculia

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Developmental dyscalculia (DD) is a specific learning disability affecting the acquisition of school-level mathematical abilities in the context of otherwise normal academic achievement, with prevalence estimates in the order of 3–6% [1] . Behavioural studies show deficits in elementary numerical processing among individuals with pure DD [2,3], indicating that deficits in higher-level mathematical skills may stem from impaired representation and processing of basic numerical magnitude. Adult neuropsychological and neuroimaging research points to the intraparietal sulcus as a key region for the representation and processing of numerical magnitude [4]. This raises the possibility of a parietal dysfunction as a root cause of DD [5]. We show that, in children with pure DD, the right intraparietal sulcus is not modulated in response to numerical processing demands to the same degree as in typically developing children. This finding provides the first direct evidence for a specific impairment of parietal magnitude systems in DD during non-symbolic numerosity processing.

We used functional magnetic resonance imaging (fMRI) to investigate the neural correlates of basic numerical processing in children with pure DD in comparison to their typically developing peers. Numerosity comparison becomes increasingly difficult as the numerical distance between the comparators is decreased; suggesting an underlying, approximate representation of numerosity. This 'numerical distance effect' [6] has been shown to modulate brain activity in bilateral parietal areas in both adults [7] and children [8]. In the present study, therefore, the numerical distance between stimuli was systematically varied (see Supplemental data available on-line with this issue for details of the experimental procedures).

Eight right-handed children diagnosed with DD on the basis of standardised math scores of at least 1.5 standard deviations below the average, in the absence of any other cognitive or learning disabilities (Table S1), were compared to eight right-handed, typically developing, age-matched peers. Participants were required to select which of two simultaneously presented sets of squares contained the larger number of items. Set pairs were assigned to either close (1–3) or far distance (5–8) groups (Figure S1).

Behavioural performance data (see Table S2) were analyzed by a 2 x 2 mixed design analysis of variance (ANOVA), with distance (close *versus* far) as a within-subjects factor and group (control *versus* DD) as a between-subjects factor. This analysis revealed a main effect of distance on reaction time ($F(1,14) = 115.75$, $p < 0.001$, $\eta^2 = 0.89$) with longer response times for close distance trials, but no distance by group interaction ($F(1,14) = 2.13$, $p > 0.1$, $\eta^2 = 0.13$). A significant main effect of distance ($F(1,14) = 85.58$, $p < 0.001$, $\eta^2 = 0.86$) on the number of errors was found, with more errors in the close distance condition. Additionally, a significant group by distance interaction was found ($F(1,14) = 5.09$, $p < 0.05$, $\eta^2 = 0.27$), with DD subjects showing a greater effect of distance on response accuracy.

To assess which brain regions were differentially modulated by distance between groups, we carried out a random-effects, whole brain, voxel-wise analysis testing for group x distance interactions. Significant interactions were observed at cluster corrected threshold of $p < 0.05$ (cluster-level threshold calculated on the basis of interaction t-map thresholded at $p < 0.005$, uncorrected: see Supplemental data for details) in the right intraparietal sulcus (IPS; BA7; 33, −50, 52; k = 222 mm^3; Figure 1), left fusiform gyrus (FG; BA37; −36, −54, −13; k = 323 mm^3; Figure S2), and left medial prefrontal cortex (MPFC; BA11; −13, 54, −2; k = 199 mm^3; Figure S3).

As can be seen from the Bar chart in Figure 1, the interaction in the IPS was characterized by a stronger distance effect in the control group than in the DD group, suggesting a lack of modulation of parietal numerical processing mechanisms in response to increasing numerical task demands in DD children. The same pattern was observed in the FG, suggesting a deficient neural response in DD to the increased demand for visual segmentation of the displays as the numerical distance between the two sets of squares decreases [9]. The interaction in the MPFC region, on the other hand, was characterized by a greater deactivation in the DD group for close *versus* far distances, while showing equal positive activations in the control group. This may reflect greater deactivation of the so-called resting state network for DD children in response to greater subjective task difficulty [10]. These data suggest specific abnormalities in the functional neuroanatomy underlying numerical magnitude processing in DD. Furthermore, these results provide evidence for a link between brain mechanisms underlying basic numerical magnitude processing and the development of higher level mathematical skills, which are impaired in DD.

To date, only one neuroimaging study has investigated pure DD in children who were otherwise typically developing [11], finding no anatomically specific impairment of brain activation during nonsymbolic magnitude comparison. The contradiction between those and our new results may stem from the differences in stimulus controls between the studies. The present results are therefore the first

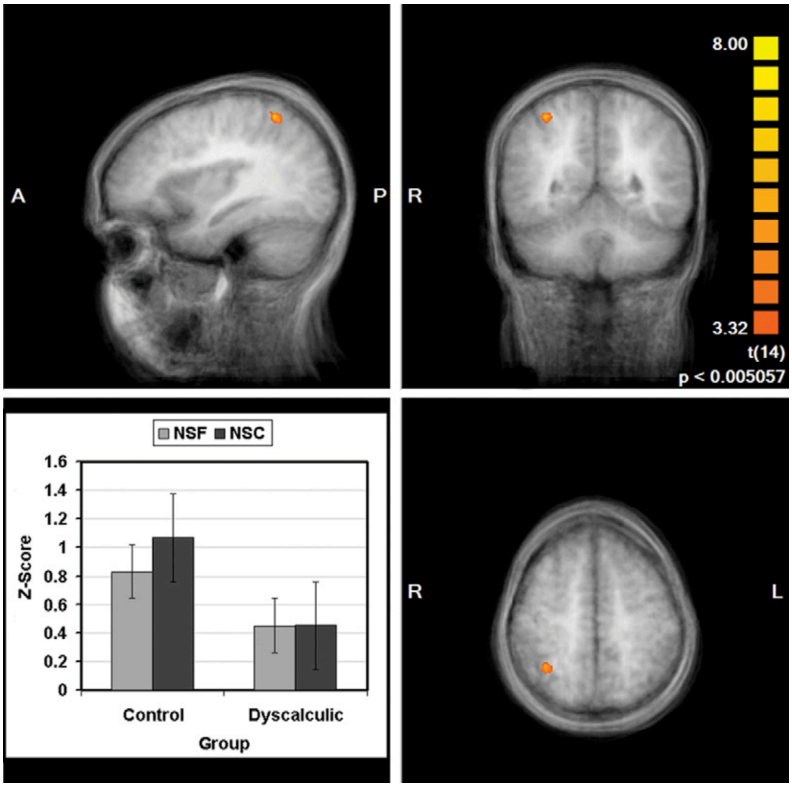

Figure 1. Interaction of group X distance in the right intraparietal sulcus.

Statistical map showing interaction of group x distance ($p < 0.05$, corrected at the cluster level) overlaid on an average image of all participants' high-resolution structural MRI scans level. The bar chart shows the parameter estimates for this region for both groups. Error bars represent the standard error of the mean. (NSC, Nonsymbolic Close Distance; NSF. Nonsymbolic Far Distance.)

to reveal atypical activation in the right intraparietal sulcus, during a non-symbolic, numerical magnitude processing task, in children with pure DD. The observed group by distance interaction in the right IPS falls within areas previously associated with processing of numerical magnitude in typically developing children [8] and adults [7], as well as within close proximity to a region referred to as the horizontal segment of the intraparietal sulcus (hIPS). The hIPS has been identified in a meta-analysis [4] of neuroimaging studies of numerical processing as being involved in the representation and processing of numerical quantity (mean Talairach coordinates for hIPS:41, –47, 48; standard deviations for these mean coordinates: 7, 7, 5).

The present results, therefore, suggest either a weakened parietal representation of numerical magnitude in DD and/or a reduced ability to access and manipulate numerical quantities. This basic numerical capacity, for which a brain-level impairment in DD is revealed here, appears to be a necessary foundation on which the development of higher level arithmetical skills is scaffolded. A recent study [12] showed that transcranial magnetic stimulation of the right parietal lobe produces behavioural patterns similar to those found in adult dyscalculics, providing a simulation of DD, and providing further evidence for the key role played by the right intraparietal sulcus in basic numerical magnitude processing. Our results, however, provide direct evidence of parietal dysfunction in pure developmental dyscalculia and thereby strengthen the hypothesis that dyscalculia is caused by ontogenetic disruption of the neural circuitry that supports fundamental representation of numerical magnitude.

Supplemental data

Supplemental data are available at http://www.current-biology.com/cgi/content/full/17/24/R1042/DC1

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