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Residual number processing in dyscalculia☆

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ABSTRACT

Developmental dyscalculia – a congenital learning disability in understanding numerical concepts – is typically associated with parietal lobe abnormality. However, people with dyscalculia often retain some residual numerical abilities, reported in studies that otherwise focused on abnormalities in the dyscalculic brain. Here we took a different perspective by focusing on brain regions that support residual number processing in dyscalculia. All participants accurately performed semantic and categorical colour-decision tasks with numerical and non-numerical stimuli, with adults with dyscalculia performing slower than controls in the number semantic tasks only. Structural imaging showed less grey-matter volume in the right parietal cortex in people with dyscalculia relative to controls. Functional MRI showed that accurate number semantic judgements were maintained by parietal and inferior frontal activations that were common to adults with dyscalculia and controls, with higher activation for participants with dyscalculia than controls in the right superior frontal cortex and the left inferior frontal sulcus. Enhanced activation in these frontal areas was driven by people with dyscalculia who made faster rather than slower numerical decisions; however, activation could not be accounted for by response times per se, because it was greater for fast relative to slow dyscalculics but not greater for fast controls relative to slow dyscalculics. In conclusion, our results reveal two frontal brain regions that support efficient number processing in dyscalculia.

1. Introduction

Developmental dyscalculia (DD) is a congenital and specific learning disability affecting the understanding of numerical concepts and mathematical proficiency in the context of normal intelligence (American Psychiatric Association, 1994). People with dyscalculia – about 4–7% of the school-aged population (Shalev, 2007) – often make counting errors, have problems in performing arithmetical procedures, use developmentally immature and usually time-consuming problem solving strategies such as verbal or finger counting, and have difficulty in retrieving basic arithmetic facts from long-term memory (see Butterworth, 2005, 2010; Kaufmann et al., 2011; Rubinsten and Henik, 2009 for reviews).

Numerical impairments in dyscalculia have often been associated with functional and structural abnormalities that mainly involve the parietal lobes. For instance, in tasks that require the comparison or calculation of symbolic (larger number: 1 or 3?) or non-symbolic quantities (larger amount: ● or ●●●?), children and adults with dyscalculia have weaker activation compared to controls in and around the intra-parietal sulcus (IPS) and in some cases the inferior and pre-frontal areas (Kaufmann et al., 2009; Kucian et al., 2006; Molko et al., 2003; Mussolin et al., 2010a; Price et al., 2007; Rotzer et al., 2008). Other studies found that adolescent and adult with dyscalculia who were premature or had genetic disorders, had less grey-matter density in the left or right IPS (Isaacs et al., 2001; Molko et al., 2003). These results have been taken to suggest that the IPS is the most critical brain area for manipulating quantities (Butterworth, 2010; Wilson and Dehaene, 2007), or for connecting numerical symbols to their quantitative referent (Rousselle and Noël, 2007; Rubinsten and Henik, 2005, but see Mussolin et al., 2010b), although a more recent view highlights the multi-componential nature of dyscalculia (Fias et al., 2013).

A closer look at these neuroimaging studies indicates that differences between dyscalculics and controls are sometimes very specific. For instance, numerically-normal participants are slower to decide which of two numbers is larger when the numerical stimuli are close in magnitude ('1' vs '2'), than distant in magnitude ('1' vs '9'), and the numerical distance between the stimuli is inversely proportional to response times (Moyer and Landauer, 1967) and to parietal activation in controls (e.g. Pinel et al., 2001), but this effect is not observed in participants with dyscalculia (Kucian et al., 2006; Mussolin et al., 2010a; Price et al., 2007). Other differences in brain activation between

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people with dyscalculia and controls are often quite subtle or even non-existent (e.g. Kovas et al., 2008), and in some cases the associated statistics do not survive a standard correction for multiple comparisons (e.g. Kucian et al., 2006; Molko et al., 2003; Mussolin et al., 2010a). There may be many reasons why differences between adults with dyscalculia and controls are not always detected. One factor may be related to the type of control tasks used in fMRI experiments, which is usually subtracted from the experimental task(s) of interest. Some control tasks involved implicit quantity processing, for example when participants were required to compare shades of colours or of grey (Kucian et al., 2006; Mussolin et al., 2010a). When subtracting these quantity-based control tasks from the experimental numerical tasks, potential differences between the tasks and between adults with dyscalculia and controls may have been cancelled out because the experimental and the control tasks are both based on quantity processing.

Since most of the current imaging studies on dyscalculia report the parietal lobes among the main areas of interest, a second factor concerns the role of these areas in response-selection and comparison processes. It is well known that parietal areas are engaged by these processes as well as numerical processes (e.g. respectively Corbetta and Shulman, 2002; Cohen Kadosh et al., 2008; Dehaene et al., 2003). We have previously been able to tease apart parietal areas related to numerical processes from those related to response-selection processes, which typically correlate with reaction times (Cappelletti et al., 2010). By factoring out response times, we identified right parietal areas that were selective to semantic processing of numbers more than words from left parietal areas linked to response-selection processes that numbers share with other non-number semantic categories. These results therefore highlight the different roles of the left and right parietal regions when processing numbers, and the importance of factoring out response-related factors when characterizing parietal activations in dyscalculia.

A third factor that may account for previous inconsistent results or undetected differences between people with dyscalculia and controls is related to individual differences in the dyscalculic sample. Dyscalculia is known to be heterogeneous (Rubinsten and Henik, 2009), although previous studies have only focused on group effects. However, these effects may potentially hide differences across individual dyscalculics. One reason why it is important to consider individual differences in dyscalculia comes from the observation that people with dyscalculia often retain some residual abilities to perform numerical and quantity tasks especially when their responses are untimed. For instance, participants with dyscalculia have been reported to be accurate at comparing the value, height or greyness of numerical stimuli, at naming numbers and at comparing the duration of stimuli (e.g. Cappelletti et al., 2011; Censabella and Noël, 2005; Kaufmann et al., 2009; Kucian et al., 2006; Landerl et al., 2004; Rotzer et al., 2008; Rubinsten and Henik, 2005). This suggests that dyscalculics may have developed strategies to overcome their quantity and number impairment. Yet, the focus of research in dyscalculia has so far been in terms of their impaired number skills observed at a group level rather than residual numerical abilities which may vary from one individual to another.

1.1. This study

To investigate the impaired brain systems in dyscalculia as well as those supporting residual number processing (defined as number accuracy not differing from controls), several methodological novelties were introduced in this study: first we used identical semantic and baseline tasks for numbers and for another non-numerical category, i.e. written object names; this allowed us to distinguish between any effect related to general semantic manipulations (such as extracting meaning from numbers symbols or names) and specific to number (like quantity manipulation). Secondly, we used a baseline control task that did not require any quantity processing but instead was a categorical colour-decision task on the identical numerical and object-name stimuli. Third, we controlled for RT-related effects similar to our previous study of numerically-normal participants (Cappelletti et al., 2010); this allowed us to identify any number-parietal activation that was not contaminated by RT effects. Fourth, as well as looking at group effects, we also examined individual differences in behavioural and neuronal profiles. Finally, we focused on adult participants with dyscalculia rather than children who are more commonly investigated (e.g. see Kaufmann et al., 2011 for a review). This allowed us to tease apart activations that may reflect developmental changes (e.g. Ansari and Dhital, 2006) from activations that more uniquely reflect number processing. For instance, frontal activations in children sometimes reflect greater reliance on attentional and working memory resources compensating for undeveloped parietal regions, which in adults support automatic processing of numbers (Ansari et al., 2005; Rivera et al., 2005).

More broadly, looking at residual numerical performance in dyscalculia may offer a perspective into brain plasticity, i.e. how the human brain is capable of adapting to cope with the need or pressure to use numbers despite the difficulties in doing so.

2. Material and methods

2.1. Participants

Overall one hundred and twelve right-handed, MRI compatible, native English speakers with normal or corrected to normal vision gave informed written consent to participate in the study. Eleven of these participants had developmental dyscalculia, the remaining one hundred and one were numerically-normal controls. The study was approved by the National Hospital and Institute of Neurology's joint ethics committee.

2.1.1. Control subjects

There were three groups of numerically-normal participants. The first group served as control for the fMRI study and one of the MRI analyses; it included twenty-two right-handed numerically-normal participants comprising twelve females with a mean age of 54.55 years. Their wide age range (22–74) provided a normal source of inter-subject variability from which to assess variability in the participants with dyscalculia. We have described the fMRI results from these control subjects in an earlier publication (Cappelletti et al., 2010). Here we used the same sample to assess normal and abnormal activation in our population of dyscalculic participants. We also used this control sample to test whether any abnormal activation corresponded to structural abnormalities using voxel-based morphometry (VBM, Ashburner and Friston, 2000).

The second control group of numerically-normal participants was recruited to increase the power of the VBM analysis when assessing structural abnormalities in dyscalculia. This group included 29 right-handed healthy females with a mean age of 42.12 years (range 24–70). The third group of numerically-normal participants comprised 50 new subjects (33 females, mean age = 35.6, range 19–76) that took part in previous studies (Cappelletti et al., under review-a,b) and that were compared to dyscalculics only in some of the out-of-scanner behavioural assessments, specifically number comparison and numerosity discrimination.

2.1.2. Adults with developmental dyscalculia

Eleven adults with dyscalculia were studied (all females; mean age: 42.82 years, range 25–70). Dyscalculia was diagnosed before participants were invited to take part in the study. The diagnosis was based on the Dyscalculia Screener (Butterworth, 2003), and corroborated by performance in: (i) a standardised mathematical task, i.e. the Graded Difficulty Arithmetic test (GDA, Jackson and Warrington, 1986); (ii) the arithmetic subtest of WAIS-R (Wechsler, 1986); (iii) a number comparison task; and (iv) a task consisting of discriminating the