Numerical magnitude assessment in dyscalculic and control individuals: an event-related PRESTO fMRI study

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Abstract: We report the results of an fMRI study using the PRESTO sequence in an event-related design to study the differences in brain activation between dyscalculic and normal subjects. Our results show that the left parietal lobe (intraparietal sulcus) is not activated in subjects with developmental dyscalculia (DC) and suggest that dyscalculics may be deficient in looking up language-coded multiplication tables.

Introduction: Developmental dyscalculia is an important learning disability, impairing the normal acquisition of arithmetic. It manifests itself by marked difficulties in the execution of the 4 base operations. Like dyslexia, approximately 5-6% of normal children are affected by DC. Dehaene, Seron and other groups3,4 found using fMRI and ERP that mental calculation activates predominantly parietal and frontal areas and supported clinical evidence for the importance of these areas in arithmetic. Moreover, Dehaene et al. showed that even simple number comparisons activate bilateral intraparietal sulci.1 It was our goal for this preliminary fMRI study to investigate if the rapid 'analogue' numerical magnitude assessing system is differentially organized in dyscalculic subjects compared to normal controls.

Methods: Subjects: 4 controls and 4 high-performing (IQ>95) dyscalculics participated in this study (6 female, 2 male, mean age 23.4±2.7y SD, 3 right-handed and one left-handed in each group). Controls had no history of neurological or psychiatric illness and denied any calculation, reading, writing or attentional difficulties. Individuals - diagnosed with DC - were taken from a large pool of affected individuals who have been prospectively followed since 1990 and assessed multiple times for various scholastic skills and neurological deficits in the framework of a epidemiological dyscalculia study.1,2 Stimuli: Subjects were exposed visually to simple multiplication problems (mostly single digit operands, e.g., 3 x 9) and had to decide if the subsequently offered solution (e.g., 32) was or far (7 f) from the calculated result (here: 27). ‘n’ had to be applied for solutions which were within a ±25% proximity to the correct result while ‘t’ was taken for solutions that exceeded this threshold. They answered by button press with the index finger of the dominant hand for ‘n’ and the middle finger for ‘t’ distances. All solutions were off from the correct value in the range of 1-20. Presentation times were the following: multiplication problem 1.3s, ISI 0.7s, solution 1.5s, answer period maximally 4s, ISI until new cycle 2s. Subjects were encouraged to respond as quickly as possible. The shortest SOA within this study design was therefore in the range of 6s and maximally 9.5s. Stimuli were displayed using an LCD back projection to a screen viewed through a mirror door. Responses: were recorded by a fiber-optic response pad system (Lumina LSC400, Cedrus) connected to the stimulus presenting and recording computer. Stimulus software was written in Matlab v6.5 running on Slackware Linux v8.1. Scanning onset was synchronized via a TTL port with the start of stimulus presentation. MRI: scanning was performed on a General Electric 3-Tesla Sigma MRI system (v3h) with the regular bird-cage head coil. Two BOLD fMRI sessions were acquired using the 3D PRESTO pulse sequence5,6: 280 scans à 2.64s, scan time 12:19min, TE40, TR26.4, matrix size 51x51x32, isomorphic voxel size 3.75mm. Analysis: Data preprocessing included discarding of the first 4 PRESTO scans, motion correction, normalization to standard MRI EPI spatial, and spatial smoothing at 8mm. The GLM model included firstly a regressor for the multiplication stimuli or for the (incorrect) solutions, and secondly, a parametric modulator column with values representing either the problem size effect (PSE) or the distance effect (DE), respectively. Statistical thresholds for the random-effect (RFX) group analysis were kept between p<0.001-0.01 (uncorrected).

Results & Discussion: Behavioural: Although the controls were slightly faster and solved more multiplication problems the error rates were similar for both groups: controls did 129.5±3.9 SD multiplication problems (error rate: 25%±1.56% SD) while the dyscalculic group performed at 113.5±7 SD (error rate: 29.3%±10.2% SD). The possibility that subjects’ frustrations about her/his failure contributed to the detected brain metabolic activations is unlikely. fMRI: The experimental setup was designed to detect brain areas which are manipulated by parametric (intrinsic) values within the number processing system during multiplication and comparison. As the baseline conditions consist practically of calculation only subtle signal changes are expected, this in contrast to experiments with proper resting conditions. The main observation is that a differential activation in favor of the control group is apparent for the left parietal lobe and left intraparietal sulcus. Only the control subjects showed here significant signal intensity changes which corresponded with the mathematical formulations of both the PSE and the DE. But both groups, conditions. The main observation is that a differential activation in favor of the control group is apparent for the left parietal lobe and left intraparietal sulcus. Only the control subjects showed here significant signal intensity changes which corresponded with the mathematical formulations of both the PSE and the DE. But both groups, controls and dyscalculics, involved the corresponding structures on the right side during numerical distance assessment. Moreover, the dyscalculics activated the left frontal mid grey as the multiplication tasks increased in problem size, in contrast to controls. This may be interpreted as a disproportional load on working memory.

Figure 1: Differential brain activation between dyscalculic and control subjects during a simple multiplication task using a rapid self-paced experiment design. The numerical problem size effect (log(a x b)) and the numerical distance effect (-log(distance from correct result / correct result)) were parametrically computed and are shown as activation clusters (*** for p<0.001, * for p<0.01). Main observation in this study was that the 4 dyscalculic subjects failed to activate the left parietal lobe during multiplication when tested for the parametric effects, this in contrast to their peers (n=4).

Problem Size Effect Distance Effect

log(PS) -log(distance/PS)
dyscalculics > controls**
dyscalculics** controls*
dyscalculics controls > dyscalculics***