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ScienceDirect
Neuroscience Letters 417 (2007) 181–186
Neuroscience Letters
www.elsevier.com/locate/neulet

A combined event-related potential and neuropsychological investigation of developmental dyscalculia

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Received 9 December 2006; received in revised form 30 January 2007; accepted 14 February 2007

Abstract

Adolescents with developmental dyscalculia (DD) but no other impairments were examined with neuropsychological tests and with event-related brain potentials (ERPs). A matched control group and an adult control group were tested as well. Behavioural and ERP markers of the magnitude representation were examined in a task where subjects decided whether visually presented Hindu–Arabic digits were smaller or larger than 5. There was a normal behavioural numerical distance effect (better performance for digits closer to the reference number than for digits further away from it) in DD. This suggests that semantic magnitude relations depend on a phenomenologically (nearly) normal magnitude representation in DD, at least in the range of single-digit numbers. However, minor discrepancies between DD subjects and controls suggest that the perception of the magnitude of single digits may be slightly impaired in DD. Early ERP distance effects were similar in DD and in control subjects. In contrast, between 400 and 440 ms there was a focused right-parietal ERP distance effect in controls, but not in DD. This suggests that early, more automatic processing of digits was similar in both groups, and between-group processing differences arose later, during more complex controlled processing. This view is supported by signs of decelerated executive functioning in developmental dyscalculia. Further, DD subjects did not differ from controls in general mental rotation and in body parts knowledge, but were markedly impaired in mental finger rotation, finger knowledge, and tactile performance.

Keywords: Developmental dyscalculia; Magnitude representation; Distance effect; Executive functions; Finger representation; Event-related potentials

Developmental dyscalculia (DD) is a cognitive disorder "affecting the ability of an otherwise intelligent and healthy child to learn arithmetic" (with relatively high-prevalence, 3–6.5%) [9]. DD appears despite normal intelligence, proper schooling, adequate environment, socioeconomic status and motivation (DSM IV). Some researchers suggest that the main factor behind DD is the impairment of general cognitive abilities, like attention and executive functioning [7]. Others hypothesize that some types of DD may be related to the dysfunction of specific number processing circuits [2]. Lesion studies have identified the parietal lobes as playing a major role in arithmetic [8]. Brain imaging experiments confirm that there is a representation of magnitude in the bilateral horizontal intraparietal sulci (HIPS, for a review see [4]). Researchers have found abnormal parietal structure and activation patterns in various subject groups with arithmetic difficulties [11–16]. These observations suggest that at least some forms of DD may be coupled with abnormal parietal structure and/or function, potentially arising as a consequence of genetic influences and heredity [18].

In a meta-analysis of fMRI findings, Dehaene et al. [5] theorized that the parietal cortex holds three representations relevant to arithmetic: (1) The representation in the HIPS codes magnitude as an analogue property of the environment. The analogue nature of this representation is reflected in its best established markers, such as the symbolic and non-symbolic numerical distance effect (DE): magnitude comparisons are easier when the to-be-compared quantities are more distant from each other, relative to when the quantities are closer to each other. (2) Bilateral posterior parietal areas may be involved in orientation to numerical information by directing attention on a spatial mental number line. (3) Language-related representations in the left angular gyrus and the left perisylvian areas play a role in symbolic processing and arithmetic fact retrieval. A recent study reported that both magnitude processing and the finger scheme

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0304-3940/$ – see front matter
doi:10.1016/j.neulet.2007.02.067

can be disturbed by repetitive transcranial magnetic stimulation of the left angular gyrus [17]. This confirms the possible relation between parietal representations relevant for number and finger representation [8].

Here, we compared DD subjects with no other deficits apart from calculation disturbances to control subjects. Since the patients were unimpaired in verbal processing and visuo-spatial skills, we assumed that their calculation problems were most probably related to the dysfunction of the magnitude representation [19], and/or to the impairments of more general executive functions. Therefore we sought whether two signatures of the magnitude representation, the behavioural DE, and its electrophysiological correlate, the event-related brain potential (ERP) DE appears in our DD subjects. ERP distance effects are amplitude modulations of the parietal P300 ERP component [10], and/or amplitude modulations of parietally measured ERPs at 200 ms after stimulus presentation [3,20]. The lack or abnormality of behavioural and/or ERP DEs in DD subjects would suggest that the impairment of the parietal magnitude representation underlies DD without verbal impairments [2,15,19]. Bearing in mind alternative theories of DD we also examined the finger knowledge, spatial skills, executive control and attentional skills of participants.

A special education institution selected DD participants from their patient pool. There were four selection criteria: (1) subjects had been diagnosed with DD more than 2 years ago, (2) they had no other diagnosed deficit than DD, and (3) they had normal socioeconomic status. (4) Further, selected DD subjects must have participated in DD therapy for at least 2 years. That is, despite participating in therapy, their impaired arithmetic performance and DD diagnosis must have remained unchanged during the 2 years previous to the study. The DD therapy was specifically tailored to children with DD, and it targeted the training of basic arithmetic skills (e.g. number comparison, number-line knowledge, simple operations and algorithms, place value). The diagnosis of DD was based on extensive testing of arithmetic skills (numerical concepts and principles, relationships, basic operations, place value, story problems, logical rules). The battery also included the Hungarian version of the Wechsler IQ scale, testing for dyslexia, dysgraphia, attention deficits, tests for spatial/temporal orientation, left/right differentiation and body-knowledge. Out of a pool of about 50 candidates with severe calculation disturbances 8 potential participants were identified (all other participants had additional impairments, like dyslexia, dysgraphia, or severe spatial disorientation). One boy ceased to cooperate during testing, this left 7 girls in the dyscalculia group (DG; mean age and standard deviation 17 ± 1.41 years). Subjects had attended neurologists, and none of them were diagnosed with neurological conditions. All subjects were highly functioning, wishing to pursue studies at university level. All DG adolescents were attending mainstream public high schools and had official statements of DD, i.e. they were not required to attend math classes but they had to learn natural sciences.

An adolescent control group was matched to DG in gender, age, verbal IQ (VQ), and school performance (CG, mean age and S.D. 16.43 ± 1.39 years). When matching participants as closely as possible on VQ, the performance IQ (PQ) of control participants was higher than the PQ of DG (this is difficult to avoid in light of the results—see later). VQ: 102.6 ± 8.8 and 109.7 ± 6.4, PQ: 94.3 ± 11.1 and 111.6 ± 5 for DG and CG, respectively. School performance was also considered in matching subjects. Marks in DG: Arts (literature, grammar, history, foreign language): 4.22 ± 0.71 (marks range from 1 to 5 in Hungary: 1 = fail; 4 = good; 5 = excellent). Sciences (biology, physics, chemistry, geography 3.26 ± 1.15). Marks in the CG (Arts 4.18 ± 0.77; Sciences 3.71 ± 1.08). In order to establish parity with earlier findings with adults, one adult comparison group was recruited (mean age and S.D. 21 ± 2.14; all college students). The study was approved by the institutional ethics committee.

Verbal, general, and basic mathematics skills of DG had been tested by one of the authors (J.D.). All DG subjects were slow and unsure in the naming and writing of numerals, especially with numbers above 100. All participants were slow and error-prone in both one and two-digit multiplications. Six out of seven DG subjects had difficulties in understanding and using place value. All subjects used fingers and other tools during counting. DG subjects recited math story problems accurately but could not translate stories into equations. Their understanding of, and memory for non-mathematical texts and reading/writing achievement were normal. All DG subjects could recognize and apply simple rules with numbers below 20 (e.g. complementing series "2, 5, 9, 14 . . ." with 20), though slowly. Participants could also understand and apply rules in non-mathematical contexts (e.g. continuing series with letters, or pictures of a scenario).

Neuropsychological tests were selected according to former results and assumptions regarding DD. Attention was measured by the Toulouse–Pieron test. In this test, subjects searched through a set of printed squares with a line attached to the squares. Out of a pool of 400 squares subjects identified squares with four predetermined kinds of line orientations. They had 5 minutes to find as many targets as possible. Performance was calculated by dividing the number of the searched items by the number of errors. Short-term auditory memory and sequential processing was measured by forward and backward digit-span. Executive control was tested by the Trail Making Test (TMT), Part A and B [1]. Finger representation was tested by a mental hand rotation task consisting of 4×20 pictures of a hand rotated by 0°, 45°, 90° or 180°. Subjects decided as fast as possible whether pictures delineated left or right hands. In a finger naming task subjects named and showed their finger touched by the investigator with eyes closed and eyes opened (3×5 problems). Tactile-perceptual abilities were measured in a task where 10 everyday objects (e.g. key, pen) were identified separately with both hands with eyes closed. Body representation was examined by a task where subjects pointed to their body parts named by the experimenter (five problems). Mental rotation was tested by Shepard's mental rotation test. Knowledge of spatial directions was tested by the question: "You are facing East. Turn right and right again. Where are you looking at now?" (one problem). Estimation of spatial relations and estimation of relative distances in space was tested by asking questions like: "What is closer to the table: the door or the window?" (object–object relation), and "What is closer to you: the TV or the table?" (object–me