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Research report

Developmental dyscalculia is related to visuo-spatial memory and inhibition impairment☆

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ABSTRACT

Developmental dyscalculia is thought to be a specific impairment of mathematics ability. Currently dominant cognitive neuroscience theories of developmental dyscalculia suggest that it originates from the impairment of the magnitude representation of the human brain, residing in the intraparietal sulcus, or from impaired connections between number symbols and the magnitude representation. However, behavioral research offers several alternative theories for developmental dyscalculia and neuro-imaging also suggests that impairments in developmental dyscalculia may be linked to disruptions of other functions of the intraparietal sulcus than the magnitude representation. Strikingly, the magnitude representation theory has never been explicitly contrasted with a range of alternatives in a systematic fashion. Here we have filled this gap by directly contrasting five alternative theories (magnitude representation, working memory, inhibition, attention and spatial processing) of developmental dyscalculia in 9–10-year-old primary school children. Participants were selected from a pool of 1004 children and took part in 16 tests and nine experiments. The dominant features of developmental dyscalculia are visuo-spatial working memory, visuo-spatial short-term memory and inhibitory function (interference suppression) impairment. We hypothesize that inhibition impairment is related to the disruption of central executive memory function. Potential problems of visuo-spatial processing and attentional function in developmental dyscalculia probably depend on short-term memory/working memory and inhibition impairments. The magnitude representation theory of developmental dyscalculia was not supported.

Developmental dyscalculia (DD) is a learning difficulty specific to mathematics which may affect 3–6% of the population. Pure DD (hereafter: DD) does not have apparent co-morbidity with any other developmental disorder, such as dyslexia or attention deficit hyperactivity disorder (ADHD), intelligence is normal, the only apparent weakness is in the domain of mathematics (Shalev and Gross-Tsur, 2001). The currently dominant neuroscience theory of DD assumes that DD is related to the impairment of a magnitude representation (MR) often called the approximate number system (ANS; Piazza et al., 2010) or a 'number module' (Landerl et al., 2004) residing in the bilateral intraparietal sulci (IPSs). This MR is

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thought to enable the intuitive understanding of numerical magnitude enabling number discrimination (e.g., Dehaene, 1997; Piazza et al., 2010). The MR theory of DD suggests that an impairment of the MR per se impacts on numerical skills leading to DD (Piazza et al., 2010; Landerl et al., 2004). The theory expects that non-symbolic numerosity comparison (e.g., comparing the number of items in two groups) is deficient in DD children. Another version of the MR theory assumes that the MR itself may be intact in DD but links between the MR and numerical symbols are impaired. This version expects that non-symbolic numerosity comparison is intact but symbolic numerosity comparison is deficient in DD (Rousselle and Noël, 2007; De Smedt and Gilmore, 2011). The MR theory of DD also claims support from neuro-imaging evidence because children with DD were shown to have lower gray matter density in the parietal cortex than controls in structural magnetic resonance imaging (MRI) studies (Isaacs et al., 2001; Rotzer et al., 2008; Rykhlevskaia et al., 2009) and they *sometimes* show different IPS activation relative to controls in magnitude comparison tasks in functional MRI (fMRI) studies. Strikingly, the MR theory of DD has never been systematically contrasted with various alternative theories proposed by extensive behavioral research. Here we report such a study.

The most established markers of the MR are behavioral ratio and distance effects (Moyer and Landauer, 1967) in symbolic (e.g., ‘Which is larger; 3 or 4?’) and non-symbolic (e.g., ‘Do you see more dots on the left or on the right?’) magnitude comparison tasks (ratio and distance effects refer to the fact that it is faster and less error prone to compare further away than closer quantities) and their correlates in the IPS (Pinel et al., 2001). To date five fMRI studies compared distance/ratio effects in DD and controls (Kucian et al., 2006, 2011; Price et al., 2007; Mussolin et al., 2010b; Kovas et al., 2009) and one fMRI study compared approximate calculation (performance on this is expected to rely on the MR of the IPS) in DD and controls (Davis et al., 2009). Behaviorally, only Price et al. (2007) reported a different accuracy distance effect in DD relative to controls. None of the studies reported a different reaction time (RT) distance effect in DD relative to controls. Price et al. (2007; non-symbolic comparison with no control task) and Mussolin et al. (2010b; one-digit Arabic number comparison with color comparison control task) reported weaker IPS distance effects in DD than in controls. Kucian et al. (2006; non-symbolic magnitude comparison with color comparison control task) compared activity in a greyscale comparison control task and in a magnitude comparison task but did not find any brain activity difference between DD and controls in either multiple testing corrected or uncorrected whole-brain analyses. Kovas et al. (2009; non-symbolic magnitude comparison with five ratios; with color comparison control task) reported DD versus control and numerical versus control task differences in various brain regions but not in the IPS and, in fact did not find any ratio/distance effects in the IPS. They concluded that the IPS based MR theory of DD may not stand. Kucian et al. (2011; non-symbolic magnitude comparison with no control task) observed differences between DD and controls in several brain areas but not in the parietal lobe and concluded that DD children have difficulty in response selection relative to control children. Davis et al. (2009) did not find IPS differences between DD and controls in an approximate calculation task.

In summary, evidence suggesting that abnormal IPS function is related to the MR in DD is weak. Four out of six studies returned negative fMRI findings with regard to the IPS based MR hypothesis of DD. Of the two positive studies, only one had supporting behavioral evidence (Price et al., 2007). However, this study did not use a control task, DD showed a normal RT distance effect, there was 17.7 points difference between DD and control on the Wechsler Intelligence Scale for Children (WISC) Block Design test, and memory/attention was not tested. Mussolin et al. (2010b) had a control task but did not have supporting behavioral evidence. The lack of behavioral evidence and control tasks leaves it unclear whether differences in IPS structure and perhaps function relate to numerical skill or to some other uncontrolled and untested function (Poldrack, 2006). In addition, each study tested a relatively narrow range of variables.

Purely behavioral studies arguing in favor of the MR theory used dot comparison tasks and showed that functional markers of comparison performance differed in DD and control participants (Piazza et al., 2010; Mazzocco et al., 2011; Mussolin et al., 2010a). However, none of these studies used non-numerical tasks controlling for non-numerical aspects of comparisons. Nevertheless, evidence demonstrates that both symbolic and non-symbolic comparison performance primarily reflects domain general comparison processes rather than properties of the number representation (Holloway and Ansari, 2008). Hence, the omission of a control task is a significant shortcoming and, in principle, studies without control tasks cannot draw any number-specific conclusions. In addition, the dot comparison task is inherently confounded by non-numerical parameters which cannot be controlled in each particular trial (Gebuis and Reynvoet, 2011, 2012; Szucs et al., 2013). Further, when tracking both numerical and non-numerical parameters in dot comparison tasks, event-related brain potentials (ERPs) only showed sensitivity to non-numerical parameters but not to numerical parameters (Gebuis and Reynvoet, 2012). Hence, in the dot comparison task participants’ supposedly numerical judgments can rely on non-numerical parameters in each particular trial. This problem also affects fMRI studies using non-symbolic magnitude comparison. It is noteworthy that Landerl et al. (2004) is one of the most often cited studies in support of the MR theory. However, that study *merely* demonstrated that DD have *slower* magnitude comparison speed than controls which can happen for many reasons. The distance effects did not differ in DD and controls and DD *only* showed a *marginally* steeper counting range RT curve than controls (pp. 117 and 119–120). In fact, the distance effect was not significant even in controls which suggests lack of power. In an extensive follow-up study Landerl and Kolle (2009) could not detect any robust basic number processing difference between DD and controls and they concluded that they ‘did not find strong evidence that DD children process numbers qualitatively differently from children with typical arithmetic development’ (ibid., abstract).

While the MR theory of DD currently dominates neuroscience research, behavioral research identified several cognitive functions which play an important role in mathematical development and proposed several alternative theories of DD