THE DEVELOPMENT OF ARITHMETIC SKILLS IN CHILDREN

PART II

ABSTRACT

Functional neuroimaging has made remarkable progress in the last years and provided new data on numerical and calculation processes. While there is a large amount of research regarding the arithmetic skills in adults, there are currently only a few functional studies approaching the arithmetic abilities in children. Although the neuroimaging studies regarding dyscalculia have provided variable results, some consistent findings have emerged so far. It is clear now that in developmental dyscalculia there is an abnormal structure and function of parietal regions. Nevertheless, further research is needed regarding the interrelation between the different aspects of arithmetic cognition as well as the breakdown of these abilities.

Key words: arithmetic skills, developmental dyscalculia, neuroimaging.

NEUROIMAGING ASPECTS IN CHILDREN WITH DYSCALCULIA

In the last 20 years, the development of neuroimaging technologies has led to high progresses in the cognitive neurosciences domain, methods such as functional magnetic resonance imaging (fMRI), event-related brain potentials (ERP) and transcranial magnetic stimulation (TMS) enabling insights into the brain regions that are implicated in a cognitive process. Regarding the arithmetic cognition, functional neuroimaging has provided new data on numerical and calculation processes, ranging from magnitude processing to calculation. Corroborated with the evidence from adult brain-damaged patients, these data provided a basis for new neurofunctional models of arithmetic cognition.

The most influential theory is the “triple code” model proposed by Dehaene and Cohen (Dehaene & Cohen, 1995; Dehaene & Cohen, 1997; Dehaene et al., 2003). The authors suggest that numbers are represented in the human brain in 3 distinct formats: as a sequence of words in the verbal code, as a sequence of Arabic numerals in the visual Arabic code and as analogical representations of number magnitude in the magnitude code. These 3 representations are linked by transcoding routes of various involvements, often in combination in calculation procedures. The verbal code is necessary for the retrieval of arithmetical facts (e.g. simple additions and multiplications), the visual Arabic code supports multidigit calculations and parity judgments and the magnitude code subserves semantic knowledge of numerical quantities being used in number comparisons and calculations. The verbal code has as its anatomical substrate a large cortico-striato-thalamo-cortical network comprising left perisylvian areas, the left angular gyrus and the left basal ganglia. The visual Arabic code is subserved by the temporo-occipital junction in both hemispheres. The magnitude representation is subserved by bilateral cortical areas around the intraparietal sulcus and both posterior superior parietal lobes, which are involved in the spatial and attentional processes relevant for magnitude representations of numbers along a so-called mental number line (for a review see Rosca, 2009a).
Different substrates are proposed for the arithmetic operations. The simple multiplications are considered rote learnt facts, being solved through a direct route by retrieval from memory via the verbal route. At the opposite pole are the subtractions that are solved through magnitude manipulations via an indirect semantic route. The additions are considered to be based both on rote memory and magnitude representations: the simple additions are hypothesized to be rote learnt facts, but the more complex additions are solved by magnitude manipulations. The data regarding the divisions is somewhat contradictory; some authors demonstrated that in order to solve a division it is necessary to access the corresponding rote learnt multiplication (Campbell, 1997) but other researchers did not observed significant improvement in solving divisions after training of multiplication tables (Rickard et al., 1994). However, these findings could be due to individual differences in arithmetic (Domahs & Delazer, 2005).

It is generally accepted now that in order to solve a complex arithmetic problem it is necessary to process the numerical information (to perceive, comprehend and produce numbers), to process the operational sign that indicates the specific calculation to be performed, to access the arithmetic facts (e.g. \(4 \times 8 = 32\), \(4 + 8 = 12\)), to execute the calculation procedures that specify the sequence of steps to be carried out in solving multi-digit operations (procedural knowledge) and to understand the arithmetic operations and principles (conceptual knowledge) (Sandrini et al., 2003). Recently, it has been proposed that the anatomical substrate for arithmetical procedural knowledge might be a left fronto-parieto-subcortical loop, in which the fronto-parietal and fronto-subcortical loops provide support for the monitoring and sequencing of the necessary steps of a complex calculation, and the parieto-subcortical loop supports the visuo-spatial working memory necessary for the representation of each sub-step of the procedure (Rosca, 2009b).

While there is a large amount of data regarding the numerical and arithmetic skills in adults, there are currently only a few functional studies approaching the arithmetic abilities in children, due to age limitations of some techniques. For example, fMRI is restricted to children of 4 – 5 years old (because the participants need to be awake and to respond to stimuli presented in a very noisy medium from the scanner).

Temple and Posner made one of the first functional studies investigating the neural basis of number processing in children. They used ERP to compare the activation of cortical areas during magnitude classification in 5 – year old children and adults and demonstrated that both, children and adults recruit parietal brain regions upon making symbolic and non-symbolic magnitude judgments (Temple & Posner, 1998). Furthermore, Isaacs et al. found reduced white matter densities in children with dyscalculia when comparing prematurely born adolescents with and without dyscalculia (Isaacs et al., 2001). In 2006, Cantlon et al. demonstrated by fMRI techniques that intraparietal sulcus is activated during non-symbolic magnitude processing in both 4-year-old children and adults (Cantlon et al., 2006) but other researchers found that children seem to rely more on prefrontal areas upon making magnitude classifications compared with adults, the parietal activations in 9 – 12-year-old children being less strong and less consistent (Kaufmann et al., 2006). Recently, functional neuroimaging studies demonstrated an aberrant activation of intraparietal sulcus in dyscalculic children upon solving symbolic number tasks such as comparison of Arabic numbers (Kaufmann et al., 2009a; Mussolin et al., 2010). The data on non-symbolic number processing is controversial: despite the key role of the intraparietal sulcus in the magnitude processing, some studies reported comparable parietal activations in children with and without dyscalculia, without group differences in the non-symbolic number comparison tasks (Kucian et al., 2006). However, other researcher found a deficient recruitment of the right intraparietal sulcus in developmental dyscalculia (Price et al., 2007). A more recent fMRI study comparing non-symbolic number magnitude processing in 9-year-old children with and without dyscalculia was suggestive for a less consistent neural activity in right intraparietal regions and compensatory neural activity in left intraparietal regions in developmental dyscalculia (Kaufmann et al., 2009b). The authors interpreted the significantly stronger activation of left intraparietal areas as reflecting compensatory mechanisms, children with functional deficits needing to recruit a wider network of regions to perform the task; furthermore, the activations are stronger in order to compensate the processing difficulties.

In the adult literature it was demonstrated that focal brain injury determines specific impairments in number processing and calculation; based on this data, researchers proposed different cognitive models for arithmetic skills. A similar approach was also pres-
ent in the developmental literature, the most widely accepted hypothesis proposing a deficient numerosity concept as the core deficit for dyscalculia (Butterworth, 2005). However, in developmental disorders it is more complicated to disentangle the deficits and to conclude if there is a causal relation between the concomitant impairments, children with dyscalculia rarely exhibiting isolated cognitive deficits in the arithmetical domain. Furthermore, developmental dyscalculia has been demonstrated to be a heterogeneous disorder, with different performance profiles both between individuals and within individuals (Dowker 2005).

An interesting study that compared the arithmetic calculations networks between children and adults was done by Kawashima and his colleagues. Using fMRI, they compared the neural substrates of addition, subtraction and multiplication in 9-14 year-old children and 40-49 years adults and demonstrated a broadly similar pattern of activation, with the involvement of the prefrontal, intraparietal, occipitotemporal and occipital cortex. However, there were also some subtle differences, children presenting a largely left lateralized activation of the prefrontal cortex while adults exhibited more bilateral activation of prefrontal areas (Kawashima et al, 2004). Rivera et al., investigating how brain activation underlying arithmetic calculations (additions and subtractions) changes between the ages of 8 and 19 years, demonstrated a decrease in activation with age in the prefrontal (dorsolateral and ventrolateral) cortex and the anterior cingulate cortex. The authors suggested that their findings could be due to the fact that younger children use additional working memory and attention to achieve similar levels of arithmetic performance with the older children (Rivera et al, 2005).

One method of studying the developmental impairments of number processing and calculation consists in investigating populations with arithmetic disturbances occurring in the context of genetic developmental syndromes such as Turner syndrome, Williams syndrome and Fragile X syndrome. For example, Molko and his colleagues, comparing the functional and structural brain changes found in Turner syndrome with normal controls, demonstrated increased activation in the bilateral intraparietal sulcus as the difficulty of calculation increased in normal subjects while the Turner syndrome subjects did not show the same pattern. Furthermore, the Turner syndrome subjects presented abnormal structural organization of the intraparietal sulcus (Molko et al, 2003). This pattern of decreased activation was also observed in subjects with Fragile X syndrome (Rivera et al, 2002). However, Kesler et al. reported that, compared with controls, children with Turner syndrome recruited additional neuronal resources in frontal and parietal regions during an easier, two-operand calculation task, whereas during a more difficult three-operand task they showed significantly decreased activation in frontal, parietal and subcortical regions than controls. The authors concluded that the dyscalculic children must recruit additional brain regions during the relatively easy task and demonstrate a potentially inefficient response to increased task difficulty compared with controls (Kesler et al, 2006).

An abnormal structure of the intraparietal sulcus, with significantly less gray matter in the left intraparietal sulcus was also reported by Isaacs and his colleagues in adolescents with deficits in calculation (Isaacs et al, 2001). Another study that compared the gray matter volume of brain tissue in subjects with and without dyscalculia revealed reduced amount of gray matter in the right parietal cortex as well as the frontal brain regions in subjects with dyscalculia (Rotzer et al, 2008).

A more recent MRI and diffusion tensor imaging study compared the macro and micro-structural impairments in 7-9 year-old children with dyscalculia to a group of typically developing children and reported robust gray matter and white matter deficits in key brain areas that have previously implicated in arithmetic cognition. Integrated analyses of brain structure using a combination of voxel-based morphometry and diffusion tensor imaging provided evidence for deficits in the dorsal and ventral visual stream. They found as key anatomical correlates of dyscalculia the right hemisphere temporo-parietal white matter, its microstructure and pathways associated with it, including most notably, the inferior fronto-occipital fasciculus and the inferior longitudinal fasciculus. The authors suggested the possibility of multiple dysfunctional circuits arising from a core white matter deficit and hypothesized that developmental dyscalculia, at its core, could be a disconnection syndrome (Rykhlueva-Kaia et al, 2009). Thus developmental dyscalculia is associated with both atypical structure and function of the intraparietal sulcus.

An interesting finding regarding the neuroimaging in developmental dyscalculia was provided by Levy and his colleagues. They reported the study of an 18 years-old severely dyscalculic male in which, the conventional MRI scans showed no abnormalities but
the magnetic resonance spectroscopy revealed a focal defect in the left temporo-parietal area, in the region of angular gyrus, including defects in metabolite amplitudes (Levy et al, 1999). This study highlighted the importance of using multiple methods to capture a particular cognitive function.

Despite the fact that the neuroimaging studies regarding dyscalculia have provided variable results, some consistent findings have emerged so far. It is clear now that in developmental dyscalculia there is an abnormal structure and function of parietal regions, but its role in arithmetical cognition is not completely elucidated.

In children, functional neuroimaging contributes to clinical diagnosis of certain neurological diseases and aids to our understanding of the development of arithmetic skills, although there are many conceptual and methodological difficulties. So far, these studies demonstrated that the circuits implicated in mathematical cognition are both structurally and functionally impaired in developmental dyscalculia. Nevertheless, further research is needed regarding the interrelation between the different aspects of arithmetic cognition as well as the breakdown of these abilities, in order to diagnose and remediate children with developmental dyscalculia and to conduct an adequate teaching of mathematics.

**BIBLIOGRAFIE / BIBLIOGRAPHY**


23. Rosca EC. Aritmetica – o perspectivă neuropsihologica. Artpress, Timişoara 2009 (a)


