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Multiple components of developmental dyscalculia

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ABSTRACT

Unresolved controversies regarding the functional impairments at the origin of dyscalculia, including working memory, approximate number system and attention have pervaded the field of mathematical learning disabilities. These controversies are fed by the tendency to focus on a single explanatory factor. We argue that we are in need of neurocognitive frameworks involving multiple functional components that contribute to inefficient numerical problem solving and dyscalculia.

1. Introduction

The debate regarding the factors underlying functional impairments at the origin of dyscalculia is longstanding. Whereas developmental dyscalculia (DD) has long been thought to be determined by multiple components, the last decade or so has seen a shift towards the search for a unique underlying factor. This tendency is plausibly related to important new findings in the cognitive neuroscience of number processing: Nieder et al. [34,35] observed number-selective neurons in the monkey brain. Neuroimaging studies suggest a similar type of neural coding in the intraparietal sulcus (IPS) of humans [39,40]. The properties of these neurons can explain human performance in great detail, in populations ranging from young infants to adults. This makes this basic number coding system a plausible phylogenetic precursor of human basic number processing skill. It has also been taken as an ontogenetic starting point for the development of more complex and schooling-induced formal arithmetic. An impaired or inaccurate quantity representation of this type, often referred to as approximate number system (ANS), is taken to be the core deficit of DD [14,27]. Alternatively, others think that DD is a weakness in automatically mapping symbols to their internal magnitude representations, reflecting a specific impairment in symbolic processing that does not necessarily impact non-symbolic processing [19,36,42,43].

This extensive focus on a single core deficit is remarkable because DD is quite heterogeneous [44,30]. Although the prevalence rates vary considerably from study to study, it is clear that dyscaculia has a high comorbidity with other learning and developmental disabilities [45] including dyslexia [5], ADHD, and dyspraxia. This naturally raises questions of how heterogeneity can be reconciled with the homogeneity which is to be expected from a single core deficit. In fact, the heterogenous nature of DD better fits theories which describe it as consequence of impairments of domain-general phenomena including working memory [24,48,12,46,37] and attention [6].

The growing focus on a core impairment in processing numerosity has led to a strong bias towards investigations of number representations as the primary explanatory factor of DD, thereby largely ignoring other critical cognitive functions and processes. Thus, many recent studies have concentrated on measuring the accuracy of number representation and related them to math achievement. Apart from the restricted scope of such a one-sided focus on number representations, it also has inherent risks, namely that representations are hard to measure independently of the attentional and decision-making processes that are involved in specific tasks. For instance, measurements of representational accuracy have been shown to be affected by attention in a number line mapping task [1] and by the decision mechanisms in a number comparison task [50,54]. Conversely, it is also true that those studies that do explicitly address processes often remain at a superficial level of explanation and only vaguely refer to cognitive processes in general terms, such as working memory or executive function, without detailed specification of the underlying neural architecture of how these functions recruit and employ representations of numerical knowledge. This vagueness may be one of the reasons why non-representational neurocognitive processes have been undervalued as key factors that contribute to both “pure” and comorbid DD.

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2. fMRI studies show that multi-componential neural networks subserve number processing and arithmetic

The neuroimaging literature of number processing has primarily focused on the parietal cortex. Although most studies have reported activity in other brain regions, these activations remained often undiscussed. The recent meta-analysis of Arsalidou and Taylor [4] has highlighted that other key subcortical and neorcortical brain regions, including inferior frontal gyrus, anterior cingulate gyrus, insula and cerebellum are also systematically related to numerical problem solving tasks. As these areas are known to contribute to basic neurocognitive functions like attentional, cognitive control and working memory these activations can be interpreted as reflecting cognitive processes providing dedicated support depending on the nature of the task and on the level of experience and development. Fig. 1 provides a schematic overview how number processing is achieved by a complex system of neural networks, each subserving specific cognitive processes. At a broad level of analysis, a number of subsystems can be distinguised. First, the integrity of visual and auditory association cortex which help decode the visual form and phonological features of the stimulus, and the parietal attention system [17] which helps to build semantic representations of quantity [2]. Second, procedural and working memory systems anchored in the basal ganglia and fronto-parietal circuits create short-term representations [31,51] that support the manipulation of multiple discrete quantities over several seconds. This system also underlies cognitive control systems that optimize performance by monitoring performance, inhibiting undesired responses etc. Third, episodic and semantic memory systems play an important role in long-term memory formation and generalization beyond individual problem attributes. Fourth, prefrontal control processes guide and maintain attention in the service of goal-directed decision making.

More broadly, it is becoming increasingly clear that cognitive skills such as mathematical problem solving depend crucially on interactions within and between large-scale brain networks [11]. Advanced imaging and analysis approaches have confirmed and refined this picture. First, it is becoming more and more clear that the parietal cortex plays multiple roles in numerical cognition. For example, Wu et al. [57] used precise cyto-architectonic mapping to show that specific subdivisions of the posterior parietal cortex make qualitatively different contributions to arithmetic. Moreover, anatomical and physiological connectivity analysis provides insights into the neural processing subserved by these regions and suggests that this functional diversity of posterior parietal cortex regions, such as the IPS and angular gyrus, is determined by distinct functional pathways that link these subregions to other parts of the brain [55].

Developmental studies in children also provide support for multi-component neurocognitive systems and indicate that math skill development is not just a matter of tuning of a single core mechanism. Cho et al. [15] demonstrated strategy-related differences between counters and retrievers in children aged 7–9 in several brain areas, not restricted to parietal cortex, thereby suggesting that the transition from using procedural strategies to skilled memory-based retrieval is mediated by reorganization and refinement in multiple brain areas. Using a cross-sectional design comparing 2nd and 3rd graders, Rosenberg-Lee et al. [41] showed that the neurodevelopmental trajectory of skill learning is accompanied with changes in brain network composition and connectivity, comprising not only parietal but also occipital, temporal and frontal areas. Using a novel multi-pronged neuroimaging approach, Supekar and Menon [47] identified for the first time the dynamic control processes underlying the maturation of arithmetic problem solving abilities. They used a novel multimodal neurocognitive network-based approach combining task-related fMRI, resting-state fMRI and diffusion tensor imaging to investigate the maturation of control processes underlying problem solving skills in 7–9 year-old children and compared it to adults. They found the anterior insula, part of a larger network of regions (related to salience processing and generating influential control signals, see Fig. 1), developed to be a major causal hub initiating control signals during problem solving by the age of 9, but still showing weaker connections to other prefrontal cortex regions, including ventrolateral and dorsolateral PFC and anterior cingulate cortex, when compared to adults. Importantly, measures of causal

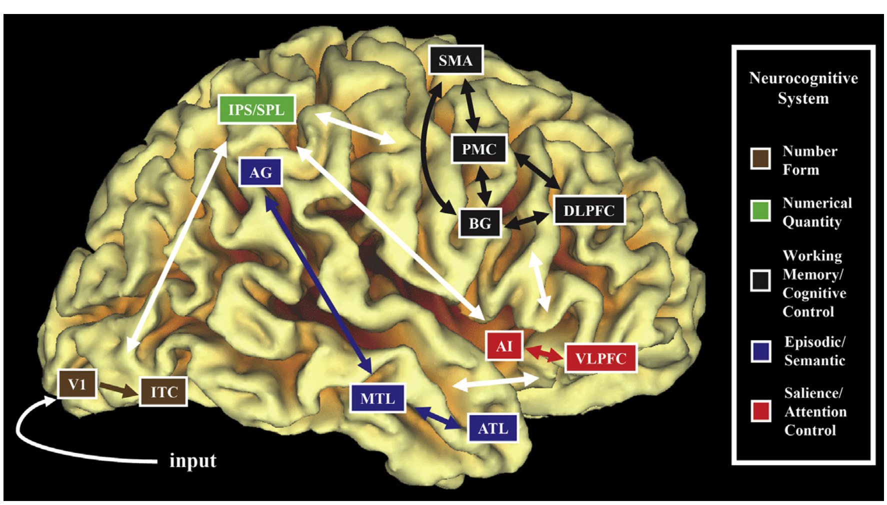

Fig. 1. Schematic circuit diagram of basic neurocognitive processes involved in arithmetic. The inferior temporal cortex (shown in brown) decodes number form and together with the intra-parietal sulcus (IPS) in the parietal cortex helps builds visuo-spatial representations of numerical quantity. Procedural and working memory systems anchored in fronto-parietal circuits involving the IPS and suparmarginal gyrus in the parietal cortex and the pre-motor cortex (PMC), supplementary motor area (SMA) and the dorsolateral prefrontal cortex (DLPFC) in the prefrontal cortex together with the basal ganglia (BG) create a hierarchy of short-term representations that allow manipulation of multiple discrete quantities over several seconds. This system also underlies cognitive control systems that optimize performance by monitoring performance, inhibiting undesired responses etc. Episodic and semantic memory systems anchored in the medial temporal cortex (MTL) and anterior temporal cortex (ATC), and the angular gyrus (AG) within the parietal cortex, play an important role in long-term memory formation and generalization beyond individual problem attributes, allowing storage and retrieval of numerical problems as facts. Finally, prefrontal control processes anchored in the saliency network encompassing the anterior insula (AI) and ventrolateral prefrontal cortex (VLPFC) guide and maintain attention in the service of goal-directed problem solving and decision making. Relative transparency for BG and MTL indicates sub-surface cortical structures. Adapted from [33].

influences between key regions could be used to predict individual differences in behavioral performance on the arithmetic task. Thus, maturing dynamic control signals from the anterior insula play an important role in attention and control during mathematical problem solving.

In sum, recent neuroimaging studies have demonstrated that multiple functional brain systems contribute to math performance and skill development. Consequently, it is highly likely that abnormal maturation or impairment of any of these systems can significnatly impact numerical abilities. Furthermore, the manner in which these neurocognitive processes are engaged depends critically on maturation of these neural systems, level of expertise in the domain, and problem complexity. However, it is not known at this time how these factors interact during academic learning

3. Neurocognitive specification: What are the multiple components?

Demonstrating that number processing is subserved by multiple brain regions is an important first step, but in itself it leaves the functional specification of cognitive subcomponents unexplained. Yet, such knowledge is crucial for understanding the nature of DD and its origin, for designing adequate diagnostic tests and for developing efficient remediation programs. Below, we review some of the cognitive functions that have been documented to be strongly related to number processing and are therefore plausible sources of mathematical disability when affected.

One of the support functions intimately related to arithmetic performance is working memory. Indeed, working memory performance measures have been shown to correlate with math performance [38,26,12,49]. Moreover, there is considerable overlap between the fronto-parietal networks typically observed in number processing tasks and in working memory tasks. Interestingly, Dumontheil and Klingberg [22] showed that task performance and intraparietal sulcus activity in during a visuospatial working memory task are were predictive of the level of arithmetic performance 2 years later. Remarkably, apart from the relatively rough functional distinction as present in the framework of Baddeley and Hitch [8] that distinguishes between verbal working memory, visuospatial working memory and the central executive [29,18], few attempts have been made to provide a detailed account of how working memory processes are related to number processing.

Behavioral studies suggest that working memory contributes to math performance by allowing the maintenance of intermediate results of arithmetical procedures or of action plans to solve complex calculations [28]. Yet, the link between working memory and math performance might be more tight and refined than the mere capacity of temporary storage. Indeed, for both working memory and the number system, the temporal and spatial order of information is a common and critical feature. Working memory does not only allow remembering pieces of information but also in which temporal or spatial order they occurred. Numbers do not express isolated quantities but quantities in ordinal relation to other numbers (more than, larger than etc.). Not surprisingly, serial order memory recruits IPS regions that overlap with those typically observed in number processing tasks [31,32]. Interestingly, Botvinick and Watanabe [10] explicitly incorporated the characteristics of number-selective neurons in a computational model of serial order processing in working memory and showed that the inclusion of such neurons provided more accurate simulations of serial working memory performance. It is likely that such processes influence numerical problem solving and engage similar neural mechanisms.

A recent series of behavioral studies [51–53] further explicitates the functional characteristics of how working memory plays a role in basic number processing tasks. These studies showed that the serial position in working memory drives the link between number and space. The interaction between number and space is further demonstrated by behavioral markers like the Spatial Numerical association of Responses Codes (SNARC) effect reflecting faster left than right hand responses to small numbers and faster right than left hand responses for large numbers ([16]. Related phenomena are the number attentional cueing effect (numbers act as a spatial cue in spatial attention tasks [23]) and the number bisection bias observed in hemineglect neurological patients (bias towards larger numbers when asked to indicate the midpoint between two numbers, [59]). Whereas these behavioral effects were originally interpreted as arising from spatial mental number line representations of numerical magnitude, the work of van Dijck et al. [51,52] indicates that it is position in working memory that is associated with space, as evidenced for instance by the fact that these effects can also be elicited by whatever information that is held in working memory [52]. These findings suggest that number processing tasks do not operate directly on information stored in long term memory, but are mediated by the dynamic organization and manipulation of items in a temporary workspace. Consequently, we predict that a reduction of the capacity to process serial order in working memory will lead to abnormalities in number processing tasks. In this respect, an abnormal workspace could be the determinant of the absence of SNARC effect and low math scores in a group of visuospatially disabled children [7]. In fact, based on the data summarized above we hypothesize that IPS activation cannot simply be taken as reflecting passive representation of numbers, but rather that it reflects dynamic working memory processes.

Just as understanding the link between working memory and numerical cognition can benefit from a detailed specification of the underlying components of working memory and how they might relate to number processing, it will be similarly important for the field to go beyond broad concepts of executive function and provide a fine-grained functional analysis of its potential role in number processing and arithmetic. In this respect, adaptive performance is an important area for further investigation. Monitoring task performance and engaging control processes to improve future performance and to avoid mistakes is a crucial aspect of executive function. This type of cognitive control has received a lot of research attention and the basic neural mechanisms have been characterized recently, with the anterior cingulate cortex and dorsolateral prefrontal cortex emerging as key regions involved in monitoring performance and subsequent adaptation respectively [9]. Importantly, neural indicators of erroneous performance not only allows self-correction of errors but have also been shown to act as a signal that drives learning in multiple domains [56]. As such, it is not surprising that suboptimal functioning of this mechanism has been related to learning and developmental disorders like ADHD (e.g. [58]). Interestingly, recent evidence suggests that a similar mechanism may also be at play during mental arithmetic. These studies have documented the adaptive processes that occur after an error has been committed at a behavioral level (e.g. [20]) and at a neural level they have shown that ACC and DLPFC become involved when errors are made [3]. The fact that the activity of some of these areas correlated with math competence is particularly informative. Investigating the neural mechanisms of adaptive performance during numerical processing can provide insights into learning and performance deficits in DD with and without comorbidities such as ADHD.

Further, cognitive control and manipulation of working memory contents is not the only executive function meaningfully related to math performance. Other candidates are worth to be considered as possible determinants of math skill and as factors contributing to DD. For instance, Bull et al. [13] observed that perseveration errors in children with weak arithmetic performance were correlated with memory retrieval errors in arithmetic tasks. This suggests that DD children may be unable to inhibit inappropriate problem solutions and mental processes. Similarly, Passolunghi and Siegel [38] observed that children with DD commit many intrusion errors in simple arithmetic which also points to the weakness of inhibitory processes in DD. Consistent with these findings De Visscher and Noël [21] reported that hypersensitivity-to-interference can be a cause of poor math performance, especially in table-related arithmetic fact retrieval. A recent large scale study based on the careful screening of more than 1000 children [49] also identified inhibitory processes and visuo-spatial working memory as key processes impaired in DD.

4. Conclusions

In this review we have outlined the view that number processing and mathematical problem solving is built on multiple neurocognitive components that are implemented by distinct and overlapping brain systems. Impairments in any of these components can compromise efficiency of numerical problem solving skills. Heterogeneity and comorbidities observed in DD and mathematical learning disability are a natural consequence of such a multicomponent system [25].

The multicomponent view stands in sharp contrast with a core deficit perspective on DD. This, however, does not imply that we ignore the importance of adequate representations of numerical magnitude. Rather, we argue that this is only one of the components that leads to math difficulties and that a biased focus on static neural representations does not account for the diversity of cognitive processes that determine an individual's math skills. The multicomponent view also calls for greater sophistication in thinking about these complexities, and there are likely no easy answers to a question as complex as the nature and origins of dyscalculia. Future research will need to focus on the construction of explicitly defined neurocognitive theories and models that describe in detail how separate cognitive functions cooperate in mathematical problem solving and how this is achieved by brain architecture and large-scale connectivity. Importantly, these models have to incorporate the dynamics of development and have to specify the changing roles of different components with developmental stage and learning.

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