Dyscalculia: neuroscience and education

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Background: Developmental dyscalculia is a heterogeneous disorder with largely dissociable performance profiles. Though our current understanding of the neurofunctional foundations of (adult) numerical cognition has increased considerably during the past two decades, there are still many unanswered questions regarding the developmental pathways of numerical cognition. Most studies on developmental dyscalculia are based upon adult calculation models which may not provide an adequate theoretical framework for understanding and investigating developing calculation systems. Furthermore, the applicability of neuroscience research to pedagogy has, so far, been limited.

Purpose: After providing an overview of current conceptualisations of numerical cognition and developmental dyscalculia, the present paper (1) reviews recent research findings that are suggestive of a neurofunctional link between fingers (finger gnosis, finger-based counting and calculation) and number processing, and (2) takes the latter findings as an example to discuss how neuroscience findings may impact on educational understanding and classroom interventions.

Sources of evidence: Finger-based number representations and finger-based calculation have deep roots in human ontology and phylogeny. Recently, accumulating empirical evidence supporting the hypothesis of a neurofunctional link between fingers and numbers has emerged from both behavioural and brain imaging studies.

Main argument: Preliminary but converging research supports the notion that finger gnosis and finger use seem to be related to calculation proficiency in elementary school children. Finger-based counting and calculation may facilitate the establishment of mental number representations (possibly by fostering the mapping from concrete nonsymbolic to abstract symbolic number magnitudes), which in turn seem to be the foundations for successful arithmetic achievement.

Conclusions: Based on the findings illustrated here, it is plausible to assume that finger use might be an important and complementary aid (to more traditional pedagogical methods) to establish mental number representations and/or to facilitate learning to count and calculate. Clearly, future prospective studies are needed to investigate whether the explicit use of fingers in early mathematics teaching might prove to be beneficial for typically developing children and/or might support the mapping from concrete to abstract number representations in children with and without developmental dyscalculia.

Keywords: dyscalculia; functional brain imaging; neuroscience; finger-based calculation; mental number representations

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Introduction

Arithmetic learning disorders (developmental dyscalculia) denote circumscribed and outstanding difficulties in the acquaintance of arithmetic skills. Importantly, dyscalculia is not a unitary concept and the associated cognitive profiles might vary widely between and within individuals (for overviews see Kaufmann and Nuerk 2005; Wilson and Dehaene 2007). With an estimated prevalence of 3% to 7%, developmental dyscalculia is about as frequent as developmental dyslexia (APA 1994) and, similar to dyslexia, persists into adulthood if untreated (Shalev and Gross-Tsur 2001). It is widely agreed that dyscalculia is a highly familial disorder (the risk for siblings of children suffering from dyscalculia is five to ten times higher than in the general population: Shalev et al. 2001). Though developmental dyscalculia may present as a single-deficit disorder (e.g., core deficit of ‘number sense’: Landerl, Bevan, and Butterworth 2004; for a review see Wilson and Dehaene 2007), many affected children exhibit associated cognitive problems, both within and outside the numerical domain (for respective overviews see Kaufmann and Nuerk 2005; Shalev and Gross-Tsur 2001). The frequent occurrence of comorbidities coincides with recent findings reporting a substantial genetic overlap between various developmental learning disorders such as dyscalculia, dyslexia and attention-deficit hyperactivity disorder (Plomin, Kovas, and Haworth 2007). Nevertheless, dyscalculia research is much younger than dyslexia research and most of what is known is derived from adult studies involving mature brain systems. Hence, our current understanding of the behavioural manifestations and (neuro)cognitive foundations of developmental dyscalculia remains incomplete.

The main aim of this paper is to demonstrate the need to go beyond adult calculation models when attempting to account for the peculiarities of developing brain systems and developmental disorders such as developmental dyscalculia. Moreover, the paper aims to illustrate how findings from brain imaging studies may inform educational understanding and even classroom instructions/interventions. The example discussed here concerns the association between fingers and numbers which has not been considered explicitly in adult calculation models, but which nevertheless – as we shall see – plays a fundamental role in learning to count and calculate. Butterworth (1999) merits reward for initiating the greatly renewed neuroscientific interest in the potential importance of finger use for the acquaintance of numerical skills. According to Butterworth (1999), fingers are convenient and natural tokens to represent number magnitudes which are intuitively used by young children when learning the verbal counting sequence and/or when executing first simple additions and subtractions (see also Butterworth 2005). Moreover, even adults may use finger-based back-up strategies. Thus, it may be argued that finger-based number representations and finger-based calculation are deeply rooted in human ontology and phylogeny. Indeed, converging evidence from brain imaging findings corroborate the latter notion of a neurofunctional link between fingers and numbers (Andres, Seron, and Olivier 2007; Kaufmann et al. 2008; Sato et al. 2007; Thompson et al. 2004). Before presenting the respective findings and their potential educational implications in more detail, we present a brief overview of current conceptualisations of typical and atypical developmental pathways of numerical cognition (as derived from neuropsychology and neuroscience).

Current conceptualisations of numerical cognition and developmental dyscalculia

Infants as young as 4–6 months are able to make number-based discriminations and even exhibit additive expectation behaviour (up to set sizes of three objects: Wynn 1992, 1995).
Larger set size discriminations may be mastered, too, provided the ratio of the to-be-compared object sets is large enough (e.g., babies may discriminate 8 from 16, but not 8 from 12 objects: Xu and Spelke 2000; and even 16 from 32 objects, but not 16 from 24: Xu, Spelke, and Goddard 2005). Interestingly, when continuous stimulus characteristics such as contour length and total filled area are controlled, 6-month-old babies can successfully discriminate large, but not small, numerosities (Xu, Spelke, and Goddard 2005; see also Xu 2003). Consequently, Xu (2003) and Xu, Spelke, and Goddard (2005) propose the existence of two core systems for number magnitude representation in infants: one mediating small (exact) and the other supporting large (approximate) numerical magnitudes (see also Feigenson, Dehaene, and Spelke 2004; for a similar distinction in mature brain systems see Dehaene and Cohen 1997).

In verbal individuals (i.e., children who have begun to master language) numerical concepts emerge as soon as children use counting to refer to objects. Upon entering formal education, most typically developing children demonstrate a rudimentary understanding of number relations, are able to count up to 20 and may even master simple additions and subtractions verbally when allowed to use their fingers or other reference objects. Thus, upon starting school (at age 6 in most European countries), most children already have acquired some verbal counting and calculation skills, which are considered to be the foundations for establishing more advanced school mathematics.

But what do we know about the development of these number processing and calculation skills during infancy and preschool years? How do children develop quantity knowledge and number representations? Which neurocognitive processes and mechanisms come into play when children gradually acquire abstract (symbolic) number representations during formal schooling? And which difficulties – within and outside the numerical domain – accompany developmental dyscalculia? These latter questions are at the core of current research attempts aiming to delineate the developmental pathways of numerical cognition. However, dyscalculia research is relatively young and, in the absence of an empirically validated developmental calculation model, many neuropsychological studies targeted at gaining a better understanding of the developmental pathways of typical and/or atypical numerical cognition rest on adult calculation models (e.g., Dehaene and Cohen 1995; Dehaene et al. 2003; McCloskey, Caramazza, and Basili 1985).

According to popular adult calculation models, number processing and calculation is multi-componential and the components constituting the calculation system are thought to be modularly organised (Dehaene and Cohen 1995; McCloskey, Caramazza, and Basili 1985). The modularity assumption derives from adult cognitive neuropsychology which considers double dissociations as evidence for a modular architecture of (neuro)cognitive systems and/or mental representations (Shallice 1988). For example, a double dissociation is present if cognitive ability A is preserved while ability B is deficient in one individual, and in another individual the opposite pattern emerges (i.e., preserved ability B and deficient ability A). Probably the most popular adult calculation model is the so-called ‘triple code model’ of numerical cognition (Dehaene and Cohen 1995) postulating three modularly organised but interrelated calculation components (i.e., analogue magnitude representation, auditory verbal word frame, visual Arabic number form), each of which is thought to be supported by distinct brain regions. A consistent finding in the adult literature concerns the key role of the intraparietal sulcus (IPS) for number magnitude processing (for an overview see Dehaene et al. 2003; Hubbard et al. 2005).

Up to now, numerous (mostly adult) studies have been published taking the Dehaene calculation model (Dehaene and Cohen 1995, 1997) as a starting-point upon which to test their hypotheses (for respective reviews see Dehaene et al. 2003; Hubbard et al. 2005; see
also for developmental issues Kaufmann and Nuerk 2005; Wilson and Dehaene 2007). However, because of crucial differences between developing and mature brain systems, adult models may not provide adequate theoretical frameworks for investigating developmental disorders (see Bishop 1997; Karmiloff-Smith 1992). For example, double dissociations in developmental disorders need not necessarily reflect the presence of modularly organised neurofunctional networks (Karmiloff-Smith 1997; Pennington 2006). Indeed, double dissociations have been observed in non-modular cognitive architectures as well (i.e., in the case of dyslexia the double dissociation between phonological and surface dyslexia; Harm and Seidenberg 1999; Plaut 1995).

Behavioural studies suggest that number magnitude discrimination abilities may be an innate capacity inherent to infants (Wynn 1992, 1995; Xu and Spelke 2000; Xu 2003) and even non-human species (Brannon and Roitman 2003), yet the question arises whether number magnitude processing is supported by identical brain regions in infants and adults. Although present developmental findings are consistent with a neurofunctional link between intraparietal regions and number magnitude processing, there is some controversy regarding the age-dependency of intraparietal (IPS) involvement in the formation of arithmetical skills. While some findings reveal similar activations in intraparietal regions extending across different ages during number magnitude processing (symbolic number processing: Temple and Posner 1998; non-symbolic number processing: Cantlon et al. 2006; Temple and Posner 1998), other studies suggest that the functional specialisation of the IPS for number magnitude processing increases with age (non-symbolic number processing: Ansari and Dhital 2006; symbolic number processing: Ansari et al. 2005; Kaufmann et al. 2005, 2006; Rivera et al. 2005). These conflicting results may partly be explained by methodological differences between studies, making a direct comparison across studies (and paradigms) difficult. Alternatively, and as mentioned already above, one may claim that adult models (resting on modularity assumptions) are not apt to account for the complexity of developing brain systems.

Developmental dyscalculia: single- or multiple-deficit views?
Upon adopting Dehaene’s modularly organised adult calculation model (Dehaene and Cohen 1995; Dehaene et al. 2003), some researchers propose that the neurocognitive underpinnings of developmental dyscalculia are best conceptualised as a (single) core deficit of ‘number sense’ (e.g., Butterworth 2005; Landerl, Bevan, and Butterworth 2004). The core deficit hypothesis implies that children diagnosed with developmental dyscalculia display specific difficulties to mentally represent and manipulate (non-symbolic) number magnitudes. Consequently, the core deficit of ‘number sense’ is thought to be related to a malfunctioning of intraparietal brain regions (i.e., the horizontal segment of the intraparietal sulcus (HIPS), which is supposed to mediate number magnitude processing according to Dehaene et al. 2003). In an excellent review, Wilson and Dehaene (2007) revisit this strong single-deficit view of developmental dyscalculia by arguing that the core deficit of ‘number sense’ may be only one of several possibly underlying deficits. According to Wilson and Dehaene (2007), other potential subtypes of dyscalculia – each of which being supported by distinct brain regions – may rest on (1) deficient verbal symbolic representations (manifesting themselves as arithmetic fact retrieval difficulties); (2) deficient executive functions (hampering fact retrieval as well as complex calculation); or (3) deficient spatial attention (leading to impaired quick recognition of small numerosities and possibly negatively affecting non-symbolic and symbolic number manipulations). Thus, Wilson and Dehaene (2007) propose that the behavioural
characteristics of developmental dyscalculia – and their neurocognitive underpinnings – might vary substantially between individuals, thus seriously questioning a strong single-deficit view.

Another argument challenging the single-deficit view of developmental dyscalculia is the observation that many children exhibiting problems in learning to count and calculate also have difficulties in other cognitive domains. Even within the arithmetical domain, children display quite distinguishable performance profiles (both at an intraindividual and interindividual level of analysis: Dowker 2005). Consequently, various attempts to classify developmental dyscalculia at a behavioural level have been undertaken (e.g., Geary 2000; Temple 1989, 1991; Von Aster 2000). As early as 1991, Temple reported a double dissociation between arithmetic fact retrieval (e.g., number fact knowledge such as $3 \times 5$) and procedural knowledge (‘knowing how’ to solve a complex arithmetic problem) in developmental dyscalculia (however, see for a critical discussion of double dissociations in developmental disorders Pennington 2006). The distinction between arithmetic fact and procedural knowledge was first acknowledged in the adult calculation model proposed by McCloskey and colleagues (1985). Likewise, the theoretical foundations for Geary’s (2000) and Von Aster’s (2000) efforts to classify developmental dyscalculia were grossly based on the Dehaene calculation model (Dehaene and Cohen 1995). A commonality of the latter classification attempts is their effort to further differentiate developmental dyscalculia according to specific performance profiles, which in turn imply the existence of distinct single cognitive deficits. And yet, according to Pennington (2006), any attempt to link these deficits to one – and only one – underlying neuroanatomical (and/or genetic) underpinning is likely to fail. Rather, developmental dyscalculia should be regarded as a complex and dynamic developmental disorder (for similar views of dyslexia and attention-deficit hyperactivity disorder see Bishop 1997; Pennington 2006). Interestingly, and consistent with the latter view, recent findings of quantitative genetic research report a substantial genetic overlap between quite diverse cognitive (dis)abilities such as reading, language and arithmetic (Plomin and Kovas 2005; for a review see also Plomin et al. 2007). This genetic overlap may partly explain the repeatedly reported high incidence of comorbidity of developmental disorders such as dyslexia, dyscalculia and attentional disorders (for a review see Kaufmann and Nuerk 2005), and furthermore, may also partly account for the considerable diversity of neurocognitive performance within one developmental disorder (in our case, dyscalculia).

To summarise, although single-deficit models (e.g., core deficit of ‘number sense’: Butterworth 2005; Landerl, Bevan, and Butterworth et al. 2004; ‘number fact dyscalculia’: Temple 1991) are presently predominant in the neuropsychological literature – probably because they are simpler and hence more testable – multiple-deficit models of developmental dyscalculia seem to better fit our current understanding of the complex nature of developmental disorders. Thus, a change of paradigms from a modular and single-deficit view towards a dynamic, process-oriented and multiple-deficit view seems to be essential for the development of empirically validated developmental calculation models, as well as for the production of mathematics curricula meeting children’s neurocognitive development (i.e., maturation-dependent readiness to grasp number-based concepts and skills) and the generation of tailored dyscalculia intervention programmes.

Neuroscience and education: the case of developmental dyscalculia

A frequent criticism of brain imaging studies involving learning is their restricted applicability to education and classroom interventions. Indeed, the great majority of
neuroscientific research – including the realm of numerical cognition and/or developmental dyscalculia – is targeted at basic research. As neuroscience is a rather young discipline, which is further tightly connected to recent technological advances (and which underwent and still continues to undergo dramatic changes within very short periods), early respective studies are hardly comparable to more recent ones (regarding both methodological and practical issues). Further, it is important to acknowledge that significant activations reported in imaging studies reveal brain regions modulating a specific task which is not equivalent to regions being necessary to process the task at hand. In addition, and partly because of methodological and technical constraints, experimental paradigms generally focus on islets of skills rather than learning processes and mechanisms, the latter being a greater focus of interest for educational researchers and classroom teachers. In general, imaging studies are only as good as the behavioural paradigms they are implementing. Hence, the development of adequate behavioural paradigms should be based on a sophisticated understanding of the interplay between neurocognitive (including genetic) and pedagogical factors determining typical and atypical trajectories within particular cognitive domains (i.e., in our case, numerical cognition).

Recently, researchers of both disciplines (i.e., neuroscience and education) are slowly becoming aware of the urgent need to ameliorate communication and to foster common research efforts. The latter focus is reflected in continuously appearing scientific articles devoted to the topic of ‘neuroscience and education’ (Ansari and Coch 2006; Fawcett and Nicolson 2007; Goswami 2004; Szucs 2005), as well as in the newly founded scientific journal Mind, Brain and Education, whose first issue was compiled in 2007. Furthermore, Fawcett and Nicolson (2007) request the establishment of a new discipline of ‘pedagogical neuroscience’. These authors emphasise that diagnostic efforts based on behavioural and/or cognitive symptoms are not sufficient to contribute to our understanding of complex developmental disorders. Taking developmental dyslexia as an example, Fawcett and Nicolson (2007) stress the need to develop brain-based theories (by employing genetic and brain-based diagnostic methods), which eventually may advance not only our understanding of developmental disorders, but also lead to tailored interventions. Hence, there is a clear need for research designs being specifically targeted at the educational implications of neuroscience research. In order to accomplish the latter goal, educational experts must share their expertise in pedagogy, and neuroscience researchers must develop ecological paradigms that are capable of investigating cognitive processes and learning mechanisms instead of circumscribed skills.

Below, I present a brain imaging study conducted at Innsbruck Medical University which was aimed at making a first step towards bridging the gap between neuroscience and education (Kaufmann et al. 2008). Although the main aim of our study was to elucidate the link between non-symbolic numerical and spatial processing, here I will focus on the numerical task only and the potential implications for educational sciences that arose from studying it. The numerical task required participants to make simple number comparisons. Stimuli were pictures of two hands, each hand showing a different finger pattern (e.g., the right hand raising three fingers, the left one two fingers). Thus, our experimental paradigm provoked finger-based counting/number discriminations and these helped us address some questions regarding the association between fingers and numbers. Before discussing the results, I briefly present the relevant literature that led us to formulate our working hypotheses.
Fingers and numbers

Empirical evidence for a link between fingers and numbers is derived from developmental behavioural studies (Fayol, Barrouillet, and Marinthe 1998; Gracia-Baffaluy and Noel 2008; Landerl, Bevan, and Butterworth 2004; Noel 2005; Sato and Lalain 2008), patient studies (Gerstmann syndrome: Gerstmann 1940; developmental Gerstmann syndrome: Benson and Geschwind 1970; Suresh and Sebastian 2000) and brain imaging studies (fMRI: Simon et al. 2002; Thompson et al. 2004; TMS: Andres, Seron, and Olivier 2007; Roux et al. 2003; Rusconi, Walsh, and Butterworth 2005; Sato et al. 2007).

Probably the earliest report of a neurofunctional association between fingers (i.e., finger discrimination) and number processing was provided in 1940 by Gerstmann, who described a patient with a right posterior parietal lesion accompanied by symptoms combining finger agnosia (difficulties to recognise and discriminate fingers), acalculia (outstanding calculation problems), right–left disorientation and agraphia (impaired writing: see Benton 1997; for descriptions of developmental Gerstmann syndromes see, e.g., Benson and Geschwind 1970; Suresh and Sebastian 2000).2

Associations between fingers (finger gnosis) and calculation skills have also been reported in developmental behavioural studies. For instance, in typically developing preschool children, neuropsychological test scores (including finger recognition and finger discrimination) were found to be a good predictor of calculation skills one year later (Fayol, Barrouillet, and Marinthe 1998). Furthermore, the findings of Noel (2005) revealed that finger gnosis seems to be a specific predictor for numerical abilities and further suggest that the link between finger gnosis and arithmetic is not restricted to tasks relying on finger-based magnitude representations (but rather encompasses a wide range of number processing tasks). Noel (2005) argues that the latter findings are best explained by the anatomical vicinity of brain regions supporting finger gnosis and those mediating number magnitude processing and calculation.

Consistent with the latter suggestion, results of a functional magnetic resonance imaging (fMRI) study (Simon et al. 2002) revealed neighbouring and partly overlapping activations in posterior parietal brain regions for quite diverse abilities such as arithmetic and goal-directed hand movement (grasping/pointing), among others. In particular, brain regions supporting grasping (postcentral gyrus and anterior IPS) were found to border those mediating calculation (in and around the (H)IPS: see Simon et al. 2002, figure 2; for a review, see also Hubbard et al. 2005).

Further corroborating the notion of a neurofunctional link between finger use and number processing are the results of a repetitive transcranial magnetic resonance (rTMS) study revealing that both finger movements and number magnitude judgements (Arabic digits) are disrupted by left parietal stimulation in adults (i.e., angular gyrus: Rusconi, Walsh, and Butterworth 2005; see also Roux et al. 2003). Finally, two recent TMS studies assessing corticospinal excitability in hand muscles are suggestive of (1) a special role of right-hand muscles (left hemisphere) for small numerals (1–4, which were interpreted as reflecting culturally acquainted embodied finger counting strategies: Sato et al. 2007; for consistent behavioural findings see Sato and Lalain 2008); and (2) of a link between hands (but not arms and/or legs) and enumeration (numbers and letters: Andres, Seron, and Olivier 2007). Interestingly, upon investigating 16- and 17-year-old adolescents with and without a diagnosis of developmental dyscalculia (DD), Soltész and collaborators (2007) report that electrophysiological responses upon performing a simple, one-digit number comparison task were not comparable between the two groups (though both groups displayed comparable behavioural performance on this task). In particular,
and most interestingly, relative to their non-DD peers, individuals with DD displayed very specific neuropsychological performance profiles being characterised by preserved mental rotation and body part knowledge (among others) but deficient performance on mental finger rotation and finger knowledge. Thus, the latter results provide the first evidence that, in DD (or some groups of DD), deficient finger knowledge may be associated with atypical brain mechanisms for performing a basic numerical task.

The latter results are clearly exciting, but it has to be noted that all respective brain imaging studies were performed on adults and hence provide information about mature brain systems only. Indeed, despite converging behavioural evidence for an association between finger gnosia and numerical skills in children (e.g., Fayol, Barrouillet, and Marinthe 1998; Noel 2005; Sato et al. 2007), respective developmental brain imaging studies are so far lacking. This gap in the research provided our motivation for conducting a developmental fMRI study that required 8-year-old children (and young adults) to make number magnitude judgements. More specifically, we presented stimuli that consisted of pictures of two hands representing different numerosities (i.e., finger patterns). Participants were asked to indicate, by pressing a button, which hand displayed more fingers. Thus, by provoking finger-based comparison strategies, the experimental paradigm required participants to make (non-symbolic) numerical classifications.

Besides number discriminations, participants were asked to make spatial and colour discriminations, too. As a thorough discussion of this research clearly goes beyond the scope of the present paper, results and educational implications presented here will focus on the following questions: (1) do elementary school children and adults recruit identical brain regions upon solving a simple number comparison task (provoking finger-based number representations)?; and (2) is there a neurofunctional link between finger-based number representations and counting/number comparison, and if so, is there an age-related change in cerebral activation patterns related to finger-based magnitude extraction?

Results revealed highly interesting findings. Behaviourally, children and adults performed at ceiling upon making number classifications (99.3% correct). However, compared with adults, children were significantly slower (746 ms and 1017 ms respectively), although response latency patterns for different types of pairs were again comparable between age groups. In particular, both age groups were significantly quicker to classify distant relative to adjacent number pairs (i.e., displaying shorter response latencies upon comparing 1 versus 5 relative to 1 versus 2: children $p < 0.05$; adults $p < 0.001$). The latter reaction time phenomenon has been coined the ‘distance effect’ and is thought to reflect the integrity of the mental number line (Dehaene 1991). Thus, the behavioural data suggest that the task was performed flawlessly by both groups (as reflected by very high accuracy rates) and, moreover, children and adults alike processed number magnitude all the way down to the semantic numerical level (as reflected by the presence of the distance effect). However, a different picture emerged regarding brain activation patterns. In particular, activation patterns in response to non-symbolic number processing were clearly distinguishable between children and adults. Relative to adults, children recruited additional brain areas in lateral portions of anterior IPS, as well as in adjacent regions of the right post- and precentral gyrus upon making finger-based number magnitude classifications. Most interestingly, the latter regions were found to be deactivated in adults. We interpret our findings as being suggestive of an age-dependent neurofunctional link between areas supporting finger use and non-symbolic number processing (Kaufmann et al. 2008). Importantly, the latter findings imply that even in the case of comparable behavioural performance between children and adults, brain activation patterns need not be identical across age.
Potential educational implications of our findings

Our findings provide evidence for an age-dependent link between finger-use and number processing that is not only interesting for neuroscience and numerical cognition research, but may also have significant implications for educational research and even classroom teaching. The demonstration of age-dependent activation differences when solving a simple number comparison task (which was performed at ceiling by both children and adults) emphasises the importance of going beyond behavioural (performance) issues. Our findings highlight the potential benefit of incorporating our steadily increasing understanding of developing neurofunctional systems into efforts to design adequate and timely pedagogical curricula. In other words, although children may succeed in solving a particular (numerical) task as well as adults in terms of performance, children may need to put more effort than adults into orchestrating the brain regions associated most closely with the task. For instance, as illustrated above, a simple number comparison task requires 8-year-old children – but less so adults – to recruit brain areas supporting finger use, thus revealing age-dependent processing mechanisms at a neural level.

With respect to classroom teaching, the implications of the latter findings are straightforward. As brain areas mediating finger use might be co-activated whenever children need to access mental number representations, it does not seem advisable to forbid children using their fingers upon performing arithmetic problems. Rather, educators and teachers could take advantage of the fact that fingers may serve as concrete embodied tokens to represent number magnitude. Moreover, fingers mirror the base-10 number system, and moreover, are readily available to be used as back-up strategies. Thus, it is plausible to expect that the consistent use of fingers could positively affect the formation of mental number representations (by facilitating the mapping from concrete non-symbolic quantity knowledge to abstract symbolic number processing) and thus also the acquisition of calculation skills. Indeed, preliminary evidence supporting the latter claim comes from a recent intervention study demonstrating that training finger gnosis significantly improves arithmetic performance in 1st-graders (Gracia-Baffaluy and Noel 2008). Moreover, a prospective study of elementary school children revealed a predominance of split-five calculation errors (i.e., solutions deviating ± 5 from the correct result: Domahs, Krinzinger, and Willmes 2008). The latter authors interpreted their findings as reflecting ‘failure to keep track of “full hands” in counting or calculation’ (abstract: Domahs, Krinzinger, and Willmes 2008). Interestingly, with increasing age/schooling (i.e., grades 1 to 3) split-five errors decreased, thus suggesting that children’s reliance on mental finger patterns (whole hand/five fingers) decreases with increasing schooling/calculation proficiency.

Finally, it is not far-fetched to argue that the explicit incorporation of finger-use in numeracy intervention programs could be beneficial for the establishment of mental number representations in children suffering from developmental dyscalculia. However, in the absence of respective empirical studies, the latter claim thus far remains speculative.

Last but not least, it is important to stress that finger knowledge is not the whole story to becoming good at maths. Rather, several other skills like abstract thinking (e.g., facilitating the mapping process between concrete and symbolic arithmetic), spatial skills (enabling the formation of a spatially oriented mental number line and, moreover, our understanding of the base-10 system of the Arabic number system), working memory (enabling us to manipulate quantities when solving arithmetic tasks, to monitor multi-step procedures, etc.), language proficiency (underlying counting routines and arithmetic fact retrieval, among others) are also considered to be important for becoming a proficient calculator. Each of the latter domains is likely to mediate the acquisition and/or application of arithmetic skills and future – preferably longitudinal – research endeavours.
are needed to elucidate their impact on the development of numerical cognition (for a review see Kaufmann and Nuerk 2005; Wilson and Dehaene 2007).

To summarise, although the study described here nicely demonstrates the usefulness of tailoring research questions to pedagogical demands with respect to a core numerical skill, there is a clear need for future (prospective) research designs targeted at more complex learning processes and mechanisms within the realm of numerical cognition. The most sensible way to approach – and possibly achieve – the latter goal is to intensively foster scientific communication and expertise between neuroscience and education.

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Notes
1. A major disadvantage of ‘complex models’ is that they may render the verification and/or falsification of working hypotheses difficult (because they typically encompass many dependent and/or unknown variables). Hence, researchers aiming to assess complex developmental disorders are especially required to (1) formulate very clear-cut hypotheses from the outset; (2) carefully define selection criteria for their study populations; and (3) employ paradigms that have been found previously to be adequate (and testable) for the research questions of interest. Reasons for advocating ‘complex models’ are at least twofold: first, complex models readily acknowledge modulating cognitive abilities (within and outside the numerical domain: Kaufmann and Nuerk 2005; Wilson and Dehaene 2007); and second, complex models may lead to a better understanding of the link between mind (cognitive), brain (neurofunctional) and pedagogy (behavioural and educational factors) mediating the acquaintance of number processing and calculation skills.

2. Though Benton (1997) seriously questioned the entity of the syndrome by stressing that a substantial proportion of patients exhibit some, but not all four symptoms constituting the full Gerstmann syndrome, the Gerstmann syndrome has received increased interest recently.

3. Stimuli across the three tasks were identical (only instructions varying), thus enabling us to control for domain-general perceptual and response-bound processing mechanisms. The strict control of domain-general processing mechanisms is crucial in brain imaging research as the to-be-interpreted activation patterns should be attributable to task-relevant processing solely (or as far as possible). The latter endeavour is achieved by a subtraction method whereby the cerebral activation patterns obtained in response to a control task (which is preferably identical to the experimental task in all but the variable of interest, in our case, number processing) are subtracted from the activations obtained in response to the experimental task. According to the subtraction logic, only the task-relevant – hence domain-specific – activations should remain. In order to achieve the best possible match between experimental and control tasks, we created stimuli that could be used across all three task conditions. In particular, stimuli consisted of two simultaneously displayed children’s hands with coloured thumbs. In half of the trials the palms of the two hands showed in the same direction, while in the other half they did not. The spatial task required participants to judge whether the palms of the two hands were showing in the same direction or not. Likewise, in the colour condition, individuals were asked to state whether the colours of the two thumbs were identical or not. The colour task served as a true control task. The spatial task was incorporated in the study because our main aim was to disentangle spatial and non-symbolic numerical processing (Walsh 2003; for a comprehensive review on the neurofunctional overlap between spatial and numerical processing see Hubbard et al. 2005).

References


