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Foresight

Mental Capital and Wellbeing:

Making the most of ourselves in the 21st century

State-of-Science Review: SR-D4
Dyscalculia

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Summary

Low numeracy skills in general and developmental dyscalculia (DD) in particular constitute a severe handicap. This review examines the causes and behavioural manifestations of numeracy deficits, their neuropsychological correlates and the limits to our understanding of these conditions. It then goes on to describe a validated test for diagnosing DD – a specific impairment in the capacity to learn arithmetic. The challenges in educating DD children and analysing their particular intervention needs are described. Reference is also made to the impact of dyscalculia on mental health (and ill-health) and individual wellbeing.

1. Background

Low numeracy skills are a more severe handicap than most people realise. In a speech to the Confederation of British Industry on 15 May 2007, Gordon Brown expressed concern that 24% of 11-year-olds failed to reach the expected level in mathematics. He proposed a new initiative to tackle this problem, called 'Every Child Counts'. A recent cohort study of the effects of low functional numeracy, estimated at about 25% of the population, shows that it is more of a handicap in the workplace than poor literacy (Bynner and Parsons, 1997).

Men aged 30, with poor numeracy, are more than two-and-a-half times as likely to be unemployed, more than three-and-a-half times as likely to be depressed, and nearly twice as likely to be arrested (Bynner and Parsons, 2005, Table A2a). Women are similarly affected. Compared with their numerically-competent peers, fewer than half are in employment at 30 years, fewer than half are home owners, and twice as many are in poor physical health (Bynner and Parsons, 2005, Table A2b).

When low numeracy is combined with low literacy, the situation for individuals is worse (Bynner and Parsons, 2005, Table A2). Low numeracy in learners is a cause of distress, low self-esteem, stigmatisation, and disruptive behaviour in class (Bevan and Butterworth, 2007; Butterworth, 2005). It is therefore a major social, educational, and clinical problem.

A recent focus group study of 9-year-old children (Bevan and Butterworth, 2007; also quoted in Butterworth, 2005) revealed that 9-year-olds with low numeracy suffered considerable anguish during the daily mathematics lesson:

Focus Group 1 (verbatim transcripts)

Child 5: It makes me feel left out, sometimes.

Child 2: Yeah.

Child 5: When I like—when I don't know something, I wish that I was like a clever person and I blame it on myself—

Child 4: I would cry and I wish I was at home with my mum and it would be—I won't have to do any maths.

Focus Group 2

Moderator: How does it make people feel in a math lesson when they lose track?

Child 1: Horrible.

Moderator: Horrible?...Why's that?

Child 1: I don't know.

Child 3 (whispers): He does know.

Moderator: Just a guess.

Child 1: You feel stupid.

More able learners, of course, are well aware of this and often tease or stigmatise children with low numeracy:

Child 1: She's like—she's like all upset and miserable, and she don't like being teased.

Child 4: Yeah, and then she goes hide in the corner—nobody knows where she is and she's crying there.

2. Causes of low numeracy

Low numeracy can have many causes, including behavioural problems, missing lessons, poor or inappropriate teaching, and maths anxiety (Butterworth, 2005). Specific language impairment may also contribute to delayed acquisition of school arithmetic (Donlan et al., 2007). However, a principal cause of low numeracy is developmental dyscalculia (DD). Children with DD are unable to acquire arithmetical skills (DfES, 2001), despite normal opportunities to learn, and whose general intelligence appears adequate to the task (WHO, 1994). The DfES guidelines characterise DD as a number-specific cognitive deficit: 'Dyscalculic learners may have difficulty understanding simple number concepts, lack an intuitive grasp of numbers, … Even if they produce a correct answer or use a correct method, they may do so mechanically and without confidence' [p4]. Developmental dyscalculics (DD), like others with low numeracy, have difficulty in learning and remembering arithmetic facts and in executing calculation procedures. They also depend much more on 'immature strategies', such as counting on their fingers to solve problems that most children know by heart (Butterworth, 2005).

In his report on early mathematics education, Sir Peter Williams wrote:

> *"There is an acknowledgement of a growing body of opinion which cites evidence for a clinical condition, analogous to dyslexia, which may seriously impede young learners in mathematics. 'Dyscalculia', as this condition has been named, is the subject of cognitive research using sophisticated clinical investigative tools such as magnetic resonance imaging (MRI). The Department for Children, Schools and Families provides interim guidance on dyscalculia for parents and teachers, while research continues into the origin of the condition, its identification and the screening techniques. To date, the evidence is not as comprehensive as that for dyslexia and reading difficulties, but it seems likely that the analogous condition exists in the symbolism for mathematics. Here, it is important to distinguish between numbers and arithmetic, and other branches of mathematics, such as geometry. It is possible to be an intrinsically good mathematician but with an inability to perform simple calculations."*
>
> (Williams, 2008: Section 148)

DD can be distinguished from other causes of low numeracy by specialised tests that reveal a more fundamental problem in the understanding of simple number concepts. For example, DDs perform poorly on very simple tasks such as counting or selecting the larger of two numbers (Landerl et al., 2004). They may even be unable to subitise – that is, recognise numerosities up to four without counting – (Koontz and Berch, 1996), an ability that underpins the acquisition of counting skills, and counting in turn forms the basis of learning arithmetic for most children (Fuson, 1988). This suggests that DD is due to a highly specific impairment in the *capacity* to learn arithmetic. Landerl et al. (2004) found that poor arithmetic, and deficits in counting and comparing numbers, can occur in children of normal or superior intelligence, reading and memory. By contrast, other types of low numeracy, with equally poor performance on arithmetic, are entirely normal on tests of counting small numerosities and comparing numbers (Iuculano et al., 2008).

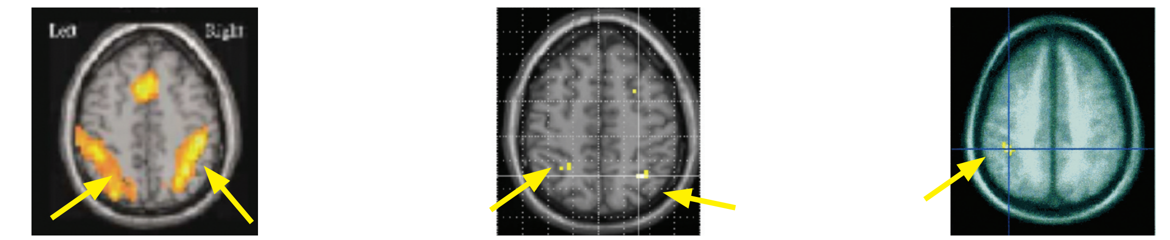
One standardised test, the *Dyscalculia Screener* (Butterworth, 2003), is designed to make the differential diagnosis between low attainment in arithmetic and DD. A deficit in processing numerosities (dot counting and number comparison) predicts unusually poor performance on arithmetic tests in children of average or superior IQ, good memory, and with no language impairment (Landerl et al., 2004). It has been proposed that this deficit is indeed the basis of DD (Butterworth, 2005), and its identification forms the foundation of the standard instrument for differential diagnosis of DD in children: the *Dyscalculia Screener* (Butterworth, 2003).

The published prevalence estimates of DD lie between 3.6% (Lewis, Hitch, and Walker, 1994) and 6.5% (Gross-Tsur et al., 1996, in Tel Aviv). This makes DD as prevalent as dyslexia, but much less recognised, and with much less support for sufferers. Like dyslexia, DD seems to be congenital and persists into adulthood (Shalev et al., 2005).

2.1. *Neurocognitive correlates of failure*

Neuroimaging reveals that arithmetic depends on a specialised brain network in the parietal lobes (Dehaene et al., 2004; Zago et al., 2001) (Fig. 1A), and on a system dedicated to sets and their cardinal numbers in the anterior intraparietal sulcus (IPS) (Castelli et al., 2006) (Fig 1B). In two abnormal populations, poor arithmetic performance is shown to be associated with abnormalities in the IPS: adults born with very low birth weight have reduced grey matter in the left IPS compared with matched controls (Isaacs et al., 2001) (Fig 1C); and in Turner's Syndrome (TS) the right IPS is abnormal (Molko et al., 2003).

Figure 1 View of the brain from above. Arrows indicate the intraparietal sulci (IPS). A. Brain areas involved in arithmetical calculation; B. brain areas selective for numerosity; C. reduced grey matter in left IPS in adults.



A. Calculation in brain   B. Numerosity processing   C. Low numeracy

Infant models. The human capacity to represent the exact numerosity of small sets and approximate numerosity of large sets appears to be present at birth (Starkey and Cooper, 1980), and the ability to perform addition and subtraction has been demonstrated in infants as young as five months (Wynn, 1992). This suggests an innate basis for numerical capacities, and would support the idea that DD may be due to a congenital deficit in this capacity.

Genetics of dyscalculia. Family studies support a genetic influence in at least some cases. If one twin is DD, then 58% of monozygotic co-twins and 39% of dizygotic co-twins are also DD (Alarcon et al., 1997), and nearly half of siblings of dyscalculics are also dyscalculic (five to 10 times greater risk than controls) (Shalev et al., 2001). Although a substantial proportion of the variance in a twin study of mathematics can be attributed to some general factor (e.g. g or 'generalist genes'), nevertheless something like a third of the variance seems to be specific to mathematical ability, though not exclusively numerical ability (Kovas et al., 2006).

X-chromosome disorders seem to affect numeracy more than other cognitive functions (Mazzocco and McCloskey, 2005; Rovet et al., 1994). Interestingly, Turner's Syndrome (X-monosomy) subjects are slower on a dot estimation task (Bruandet et al., 2004; Butterworth, 1999), and Bruandet et al. (2004) note that they are slower even with two dots; 'This suggested that many of the patients were counting within the range in which controls normally subitise. Indeed, the increase in response time from three to four dots was 237 ms in the patients, close to the value observed in the counting range, where it was only 72 ms in the controls, a significance difference'. Particularly poor number skills are also found in Fragile X (Mazzocco and McCloskey, 2005), Klinefelter's and other extra X conditions (Semenza, personal communication).

2.2. *Challenges in educating DD children*

DD causes problems for the teacher even with the introduction of Waves 2 and 3 in the National Numeracy Strategy, since there is no formal guidance as to how to identify DD learners. Many teachers want to take these children out of the Numeracy Hour altogether (Bevan and Butterworth, 2007). Here are extracts from verbatim transcripts of the interviews:

> *Teacher 1: "I think in some way there could almost be a separate programme of work for those children, – 'don't progress to this level until this has been achieved' so that it makes a bit more sense."*

The problem most often cited was not having the time to give these learners the help they need:

> *Teacher 2: "In a class of 30 I've got six. You've got a lot of problems. And when I'm on my own, I don't – I really feel very guilty that I'm not giving them the attention they need".*

However, there is a trend away from pedagogies aimed specifically at Special Educational Needs, on the assumption that general pedagogic principles will be appropriate for these learners as well. But, in fact, SEN learners are more likely to need: more intensive and explicit teaching; more practice to achieve mastery; more examples to learn concepts; more experience of transfer; more careful checking for preparedness for the next stage of learning (Norwich and Lewis, 2001); and a more personalised approach (Dowker, 2004). However, the pressure on special needs teachers is already leading to strategies to reintegrate pupils with Individual Education Plans into whole-class teaching (Frankl, 2005).

As Sir Peter Williams noted in his review:

> *"Clearly there could be far-reaching implications for teaching mathematics to the [DD] affected group, and it is important to maintain an open mind on the possible outcomes of this research. Certainly the measures proposed … to address under-attainment must take into account future developments in this field. [including] individual remedial teaching."*
>
> (Williams 2008: Section 149)

3. What do learners need?

Interventions for dyslexia are derived from a very specific understanding of cognitive deficits and neuronal abnormalities, and it has been found that targeting phonological difficulties (the core deficit in dyslexia) improves reading performance and normalises neural activity. More generally 'neural tools for comparing the efficiency of different packages for remediating dyslexia' could be developed (Goswami, 2004). Could something similar be attempted for number concepts?

4. What can be done and what needs to be done?

4.1. *Science*

Brain systems for mathematics. How the brain systems for mathematics (especially the intraparietal sulci) develop from infancy to adults is not known, either in normal or atypical development. One reason is that it is difficult to use fMRI with children (they move too much, or they fall asleep, in the scanner). EEG does not, at the moment, give sufficient spatial resolution to map the developmental trajectory, but it may be that functional Near InfraRed Spectroscopy (fNIRS) could be the answer, since it currently resolves at about 0.5 cm^2, with better resolution likely in the near future. Current systems are portable, and comfortable for young participants (see Figure 2). fNIRS measures regional cerebral blood flow, like fMRI, but unlike fMRI, at present it can only measure this in cortex and not in deeper structures. This is sufficient to see arithmetical processing (Iuculano et al., 2008) and there is now software for carrying out appropriate statistical analyses on the optical signals (Peck et al., submitted).

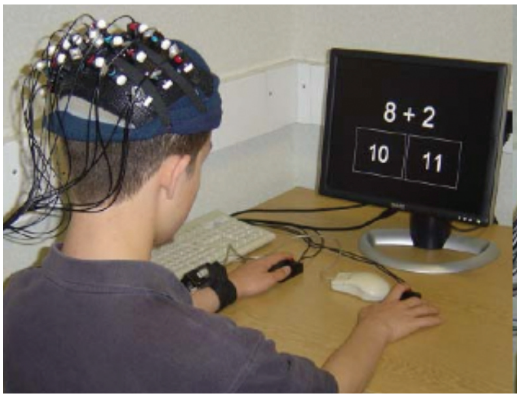


Figure 2 fNIRS. Shows young participant wearing a cap with source and detector optodes. fNIRS has several advantages over fMRI: it is more comfortable; it provides good temporal resolution (sampling at 10 Hz); it has been widely used with children from neonates onward; and it is even portable. On the other hand, the spatial resolution is much lower than fMRI (but better than EEG), and, currently, block-design experiments work much better than event-related.

<u>Differential diagnoses and subtyping</u>. It is still not clear whether DD exists in a single form with degrees of severity, or in distinct subtypes (like colour-blindness). It is also not clear how DD interacts with other cognitive abilities, including memory, language, intelligence, and spatial and motor abilities. One subtype that has been proposed is the individual with both dyscalculia and dyslexia (e.g. Jordan et al., 2002). However, to understand the effect of having a double deficit may depend critically on how each deficit is defined. So in the Jordan et al. (2002) study, the criterion was the lowest 35% on standardised arithmetic and reading batteries. Other studies use different criteria and report overlaps between the conditions of between 17% (Gross-Tsur et al., 1996) and 64% (Lewis et al., 1994). In a systematic study of basic numerical competence, no difference was observed in the numerical competence of dyslexics compared with controls, and with children with both deficits as compared with pure DD.

Prevalence. Although there have been several prevalence studies, all have used discrepancy measures based on arithmetical tests. Since there may be causes other than DD for low numeracy, a prevalence study based on a cognitively well-defined phenotype is needed. This would also assist policy-makers making provision for the condition.

4.2. *Mental ill-health*

As noted above, DD causes suffering in children, and depression and poor health in adults. It leads to poor employment outcomes, and probably to crime (rather as dyslexia does). It would be useful to have an estimate of the incidence of DD in the prison population and those sectioned for severe mental illness.

4.3. *Mental fitness and mental wellbeing*

Intervention to help DD would alleviate suffering and mental ill-health. Although the National Numeracy Strategy has raised arithmetical performance overall (DfES, 2005), and has introduced Waves 2 and 3 to help learners who are falling behind, nothing is targeted at DDs who will need special help. The best available interventions for DD have been developed for primary school children in the private sector, in part because the most effective interventions have required one-to-one teaching so that the teacher is able to adapt the current level of understanding of the child (Butterworth and Yeo, 2004).

Technology Enhanced Learning using adaptive learner models makes possible personalised learning for each DD child, even in the overstretched state sector. In principle, this could be as sensitive as a good teacher to the child's current needs. Some French research has begun using this approach with basic numerical concepts in 6-year-olds (Wilson, Dehaene et al., 2006; Wilson, Revkin et al., 2006). More generally, TEL needs to be tailored to the individual child's cognitive profile, and its effectiveness assessed with proper evaluations. Programmes for older children are also needed. The critical deficit in DD appears to be in *understanding* basic number concepts, so the value of the interventions should be judged not only in terms of trajectories of change in performance relative to existing standards, but also in terms of learners' understanding of number concepts. Moreover, neuroimaging could be used to evaluate whether the intervention creates compensatory strategies, or makes the brain operate more normally (as has been done with dyslexia intervention (e.g. Eden et al., 2004; Shaywitz et al., 2004).

4.4. *Mental development – including lifelong learning*

Standard diagnostic methods require children to carry out numerical tasks, including arithmetic or estimating the number of objects in a display. This may not work well with very young children, while a better understanding of atypical brain development and genetics in DD could allow for much earlier identification of children at risk and earlier intervention. As noted above, DD (like dyslexia) persists into adulthood. However, there is as yet no standardised test for it in adults along the lines of the *Dyscalculia Screener* (Butterworth, 2003) for children, and TEL and other forms of specific interventions could be particularly useful for adults who may find classes for elementary numeracy even more embarrassing than children do.

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