Dyscalculia

Dyscalculia is a SLD affecting the learning and comprehension of arithmetic and mathematics, in which performance is below that expected for chronological age and IQ, and also not due to poor education. Other terms have been used, such as “mathematical learning difficulty”, “mathematical disability” , “mathematical disorder”, and “developmental dyscalculia”, but these refer to the same condition (Geary, 1993; Geary & Hoard, 2001), We will use the term “dyscalculia”, as this has the most common usage.

Dyscalculia is a neurologically based mathematical learning disability characterised by a difficulty to understand simple number concepts (such as operations: + - x and /) and to acquire the numeracy skills necessary to understand and apply mathematics (for example multiplication tables and long divisions), all of which manifests in the absence of intellectual disability (Department for education and Skills (DfES, 2001).Some authors have attempted to differentiate between dyscalculia, classed as a severe difficulty with mathematics, and ‘arithmetical dysfluency’ characterised by a more general deficit of mathematical achievement. (Reigosa-Crespo et al., 2011). Whilst some have stated that arithmetic dysfluency represents a more general impairment of which dyscalculia is a subcomponent, so far studies have not found a clear differentiation between these two groups (Murphy, Mazzocco, Hanich& Early, 2007).

The prevalence of dyscalculia in school-aged children is between 4% and 10% (Peterson & Pennington, 2012), as shown by school age cohort studies (Gross-Tsur, Manor &Shalev, 1996) and population-based, retrospective, birth cohort studies (Barbaresi et al., 2005). Although this is similar to the prevalence of dyslexia, dyscalculia has received much less attention in terms of research and public interest. Yet, the effects are as profound for individuals and society (Hanushek&Woessmann, 2010, Butterworth, Varma and Laurillard (2011).

Neurobiology

In adults, the neural correlates of mathematical and numerical have been well definedprocesses (Dehaene, Piazza, Pinel and Cohen, 2003). However, studies in children are scarce and evidence for the differences in brain function between children with dyscalculia and controls is even more rare. A small review of fMRI studies in children revealed that the frontal-parietal regions are consistently reported as being involved in simple calculation processes (Kaufmann, Wood, Rubinsten&Henik, 2011). Although this review included only a limited number of studies looking specifically at the comparison between dyscalculic children and controls, the authors concluded that the differences in neural activation patterns between these two groups are very distinct. Specifically, during number comparison

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tasks, children with dyscalculia display a reduced activation of the bilateral interparietal sulci (IPS) (Mussolin et al., 2010; Rykhlevskaia, Uddin, Kondos, & Menon, 2009). However, a study by Price et al. (2007) found that the abnormal activation pattern were inthe rightIPS - not in the left. There is supporting evidence from TMS studies which have found that interrupting activity in the right parietal area in participants without any problems in numerical comprehension results in behaviours similar to those encountered in dyscalculia (Cohen et al 2007). Additionally, children with dyscalculia have been shown to recruit distributed brain regions possibly pointing towards a compensatory strategy and display a deficit recruitment of frontal brain regions (Kaufman et al. ;2011; Mussolin et al.,2010; Price et al., 2007).

Genetic

The role of heredity in the development of mathematical skill was proposed early on (Kosc, 1974). Support for this hypothesis comes from twin studies which show that in 58% of monozygotic and 39% of dizygotic twins, both siblings are diagnosed with dyscalculia (Alarcon, Defries, Gillis Light, & Pennington, 1997). Even non-twin siblings of children with dyscalculia are at an increased risk of mathematical disability, up to tenfold greater than in the general population (Shalev et al., 2001). Some chromosome disorders are also associated with dyscalculia, such as Williams syndrome (Paterson, Girelli, Butterworth, & Karmiloff-Smith, 2005) and Turner's syndrome(Butterworth et al., 1999).Molko et al. (2003) have reported abnormalities in the right IPS in people with Turner syndrome, who have particular difficulties with subtraction and large numbers. They suggest that at least in the context of Turner syndrome, abnormal IPS structure may result from an X-linked gestational problem.

Environmental

Parenting environment has also been highlighted as contributory factor in the acquisition of numeracy and mathematics. Studies assessing children and parents attitudes to learning mathematics found that parent's apprehension in relation to mathematical tasks influences their child's approach to such activities (Young-Loveridge, 1989); Aning and Edwards, 1999). In highlighting guidelines for the interventions in dyscalculia, Hannell (2005) states that parents can enable children's learning by promoting a positive attitude towards mathematics. Socio-economic status has also been linked to challenges in learning mathematics (Sammons et al., 2002).

Interventions

Since dyscalculia is a brain-based disorder, interventions trying to address these deficits should be derived from a very specific understanding of cognitive deficits and

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neuronal abnormalities. Such understanding should equally concern individuals that have to action interventions, such as administrators, parents and teachers (Goswami, 2006), as well as researchers that hope to develop them. It has already been highlighted that one of the most pertinent ways to drive research forward in this field is through interdisciplinary collaborations (Kroeger, Brown & O'Brien, 2012). Butterward and Laurillard (2010) present a broad interdisciplinary strategy for the development of such interventions (Figure 1), this emphasises the cyclical nature of interaction between the different disciplines that call equally contribute to development of targeted interventions.

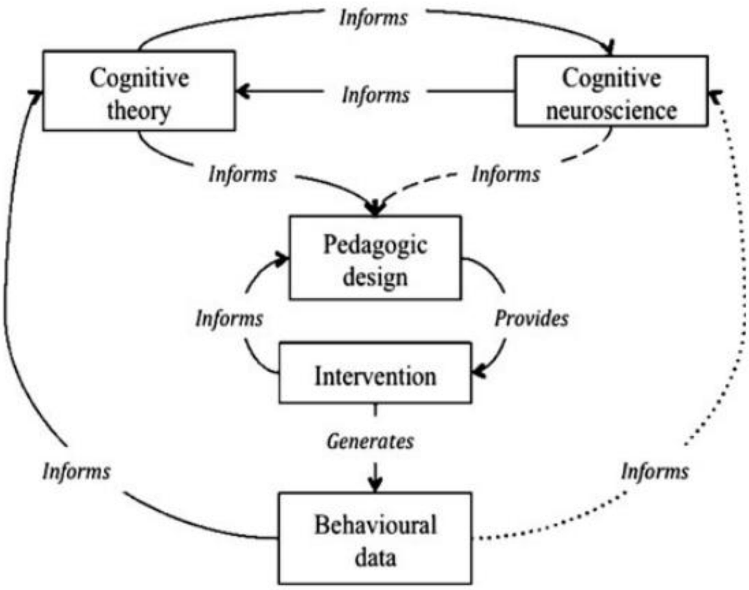

Fig. 1 Interdisciplinary strategy in the Centre for Educational Neuroscience. *Solid lines* indicate established interdisciplinary connections. *Dashed line* represents the contribution cognitive neuroscience makes in this study on pedagogic design. The *dotted line* indicates the way in which the behavioural data, in the form of neural changes resulting from intervention, can now be used to inform the neuroscience

In the following section we will review strategies known to benefit children with dyscalculia whilst also highlighting the cognitive factors they relate to. Both individual factors such as learning styles and maths anxiety as well generic impairments such as language, visuospatial and memory deficits will be mentioned.

Learning styles

Whilst children with dyscalculia will display a range of learning styles, Kay and Yeo (2003) suggest that dyscalculic learners are more likely to display a more sequential learning style (i.e. “inchworm” approach). When analysing a problem, inchworms will tend to focus on the parts rather than on the whole, they might constrain focus by using a single method, work in serially forward ordered steps and

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writing down information rather than using mental calculations. Inchworms will also tend to work mechanically and not understand procedures or values of numbers (Marolda& Davidson,2000).

This suggests that children with dyscalculia will have a preferred way of working. An awareness of learning styles can help structure and personalise interventions, but teaching strategies should not be solely focused on one style. Chin (2001) suggests that at first a child should be taught using their preferred style in order to avoid failure, but once confidence is achieved it is advisable that teaching should make use of complementary strategies. In this particular case, children should be taught to expand their focus when solving problems by being introduced to different methods in order to enhance the understanding of numbers and relationships. Children with dyscalculia are comfortable with the familiar, so any such strategies should be introduced gradually.

Maths anxiety

Dyscalculia can have detrimental impact on children's emotional attitude towards mathematics. The difficulties children encounter might affect their confidence and hence their motivation to participate successfully in activities that involve mathematics. Children with dyscalculia have been shown to display anxiety when confronted with mathematical tasks(Rubinsten&Tannock, 2010). Maths anxiety is defined broadly as a negative affective response to mathematics experienced when required to solve a mathematical problem (Tobias &Weissbrod, 1980).

In order to help learners overcome maths anxiety, effective interventions need to foster self-confidence. Hannell (2005) recommendsample opportunities to successfully practice a skill, by ensuring the level of difficulty of a problem matches the student's ability, and allowing children to select the level of difficulty they feel comfortable with. Additionally, in order to motivate students, the purpose and usefulness of mathematics should be emphasised by including activities that connects mathematics to everyday life such as counting change and going groceryshopping (Geist, 2010; Sun &Pyzdrowski, 2009; Jackson, 2008). However these must be appropriate to students life in order to be effective. Wadlington and Wadlington (2008) suggest that in order to combat maths anxiety, it is equally important to encourage students to celebrate success and allow them to map their own progress by providing chat and graphs.

Individual differencesin learning and emotional styles as highlighted above, accentuate the need to target interventions toward a child’s particular difficulties (Dowker, 2009). Individualised interventions have indeed been found to be highly effective; however a meta-analysis of single-subject design interventions in participants with learning difficulties, including dyscalculia, found that the particular method of intervention largely determines the degree of effectiveness (Swanson

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&Sachse-Lee, 2000). For example, interventions that explicitly conveyed how and why a particular strategy was being used were more successful than interventions in which the strategies being used were passively communicated. Furthermore, the effectiveness of individualised interventions have also been found to dependent on the availability of specialised training available to teaching staff (Dowker, 2009). Another downside of individualised interventions might be that they have the potential to be lengthy, although, Dowker (2009) suggests that they do not need to be very time-consuming or intensive to be effective.

Languageimapirment

Mathematical thinking is greatly intertwined with language ability. This hypothesis is supported in equal measures by neuroimaging studies which have shown that numerical tasks also activate language areas (Cipolotti, &Harskamp, 2001),by developmental studies showing that counting works are necessary for counting further than four (Gelman&Gallistel, 1978), and most interestingly by cultural studies which have found that Amazonian cultures which lack words for exact numbers larger than 5 have difficulties representing such numbers (Gordon , 2004).Although there are authors that challenge this view by highlighting that whilst language facilitates numerical concepts it does not necessarily underpin it (Gelman& Butterworth, 2005), language ability should be taken into account when developing interventions dyscalculia,as the disorder often occurs in concurrence with disturbances in the field of language (Silver, Pennett et al 1999 - Stability of arithmetic disability subtypes)

For children with dyscalculia this implies that they may not understand the language they recite and that they may not be able to use internal language to help with mathematics (Hannell, 2005). This constitutes a substantial challenge in the development of dyscalculia interventions. In order to address these deficit and enable students to communicate effectively in relation to mathematics,Wadlington and Wadlington (2008) suggest that new terms should always be explained using concrete material in order to make number concepts meaningful. Students should also be allowed to develop their own dictionaries in order to illustrate new terms. As language disability might also impair dyscalculic children’s ability to monitor thinking and learning through internal language-related thinking, interventions should prompt students to write in a journal entries in order to allow them to make sense of their successes, difficulties and thought processes(Wadlington and Wadlington (2008).

Visuospatial imapirment

Deficits in visuo-spatial skills have also been associated with dyscalculia (Geary, 2004; Szucs, Devine, Soltesz, Nobes& Gabriel, 2013). Children with dyscalculia have been found to perform worse than controls on tests of attention and visual-spatial processing (Shalev, Auerbach, and Gross-Tsur, 1995; Lindsay,

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Tomazic, Levine, and Accardo, 2001). Recently a study by Crollen and Noel (2015), compared children with high and low visual spatial ability,and found that those with low abilities performed worse in relation to basic numerical processing tasks such as number-to-position task which assesses the understanding of representations of numerical value. Consequently, children with dyscalculia may display a deficit concerning calculations which require logic dependent on holistic, spatial reasoning. As part of his Dyscalculia Toolkit, Bird (2013), suggests the use of Cuisenaire Rods in order to emphasise the relationships between numbers and therefore facilitate the construction of a coherent number system.

Visuospatial impairment in children with dyscalculia also means that they will have difficulty with shape and space. For example they might struggle with 2D representations of 3D shapes, and may find it difficult to copy or draw shapes accurately. In order to support drawing, Dowker (2009) recommends activities such as joining dots and modelling in plasticine and the use of specialist equipment when drawing e.g. rulers, templates, curves. Additionally 3-D shapes should always be presented in conjunction with 2-D representations.

Memory impairment

Multiple studies have established that children with dyscalculia experience memory deficits (Wilson and Swanson, 2000; Geary, 2004). These deficits relate to working memory as well as long-term memory. Working memory refers to the temporal capacity to process and store information. Poor working memory implies that children with dyscalculia might struggle with following instructions and as a result will need to rely on finger based representations in order to keep track of what they are doing whilst performing calculations(Hannell, 2005). They may also find it difficult to keep focused, so they will struggle to recite multiplication tables as it is easy for them to forget the sequence that they follow (Hannell, 2005). Ways to address shortages in working memory require the use of strategies and equipment which limit the requirements placed on memory during problem solving, such as calculators, concept cards, and maths videotapes (Nolting ,2000). The DynamoMaths programme (Esmail, 2008), accounts for working memory impairments by using instructions which are short, simple and repeatable (i.e. the child can listen to instructions whenever they want), and by clear providing instant feedback in order to hold the students attention and by using an uncluttered display.

Dyscalculic students also experience difficulties with long term memory imp[lying s that they struggle with remembering written symbols and correct application of procedural rules. Dowker and Morris (2014) suggest in order to reinforce learning , students should be reminded at the beginning of each session and also reminded briefly but frequently of what they had previously achieved.

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Dyscalculia guidance summary

Based on the cognitive principles highlighted above the consensus on guidelines for effective intervention in dyscalculia can be summarized as follows:

1. Interventions should be personalised according to individual needs
2. Instructions should be simple and well organised
3. Initially, abstract concepts should be made concrete
4. Big concepts should be broke down into smaller parts and introduced step by steps
5. Ample time should be allowed for students to practice new concepts, ideally students should be allowed o decide when they are comfortable to move on. Speed should not be emphasised until facts are mastered.
6. Provide pictures, graphs, charts and encourage drawing the problem in order to enable visualization of problems.
7. Provide real life examples relevant to the student's age and experiences
8. Provide immediate feedback and opportunities for students to revise their answer.
9. Allow students to communicate about mathematics in multiple ways, be it orally or through journal entries.
10. New vocabulary should be adequately explained

These guidelines are supported by the Department for Education and Skills (DfES, 2001).

Benefits of digital technologies

Interventions for children with dyscaculia have traditionally used small teacher student groups , the most popular being Numeracy Recovery (Dowker, Hannington& Matthew, 2000) and Catch Up Numeracy (Holmes &Dowker, 2013) as well as pen and paper games and toolkits (Hanell 2005; Brid, 2013) . In recent times however computerised technologies have radically changed the way children acquire information (Christakis, Ebel, Rivara& Zimmerman, 2004). As a consequence interventions for dyscalculia are moving towards digitised alternatives.

Although not specifically directed towards children with dyscalculia, computer-assisted mathematical interventions for school children have been proven to be effective since the 1960's. A review by Rasanen, Salminen, Aunio, Wilson and

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Dehaene (2009) found that computer assisted interventions have seen shown to be especially effective in primary grade because they can improve children's early mathematical knowledge by enhancing counting skills, numeral recognition, numerical concept learning.

As highlighted in the previous section, in order to be effective, interventions for dyscalculia have adhered to specific guidelines, and digital environments have been shown to mould very well with these requirements (Butterworth &Laurillard, 2010). Computerised technologies can easily be personalised to individual's needs while also enabling a self-paced learning approach which allows the individual ample opportunity for repeated practice. Additionally, digital programmes can be administered in private, so that students can manage math anxiety by making use of a threat-free tolerant approach. The flexibility to manipulate digital objects inherent in computer assisted technologies also allows students to experience multisensory instructions, which are especially important in dyscalculia (Clements, 2000) - and not provided by paper and pencil.

Examples of digital interventions which could be of help in dyscalculia

Although a range of interventions for improving mathematics ability are currently commercially available, a review of interventions for low mathematical ability found that only a small proportion of interventions are underpinned by strong neuroscience or cognitive research (Kroeger, Brown and O'Brien, 2012).The review further highlighted that only a quarter of interventions were supported by empirical evidence . Furthermore, whilst they are developed on principles known to benefit children with dysalculia, most current digital interventions are not necessarily targeted directly towards children with dyscalculia, but towards a more general group of children that present with difficulties in acquiring mathematical skill. Table 1 presents currently available programs that are based on empirical evidence and that also integrate, at least partly a digital component. The list includes both teacher led and classroom independentprogrammes.

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Table 1. List of currently available evidence based intervention programmes designed for children with difficulties in acquiring mathematical skill.

Intervention	Target population	Focus	Description	Features
The Number Race (Wilson et al., 2006)	Age 4 to 8	Focuses on number formats, counting and simple e additions and subtractions	Free adaptive software programme based on neuroscience findings related to the numerosity system in the interparietal sulci. The task requires students to select the larger of two arrays of dots focussing initially on large differences and moving on to smaller differences as the student is successful.	Adjusts level of difficulty to match learner's performance Stepwise approach
Graphogame – Math (Numerate)		Focuses on number comparison and number symbols	Finnish adaptive game based which aims to target the inherent system for representing and manipulating sets in the interparietal sulci. Task requires the comparison of visual arrays of object, focusing initially on small sets which can be counted, and moving on to tasks which require comparison processes and knowledge of verbal numerical labels.	Informational feedback Stepwise approach
Fluency and Automaticity through Systematic Teaching with Technology (FASTT Math) (FASTT Math, n.d.)	Grades 2 to 12	Focuses on developing fluency with basic mathematical operations	**Programme which includes series of engaging and motivating math games** which focus on the relationship between numerical symbols and their associations with verbal representations. By personalising learning material the programme determines the level of automaticity and builds on existing declarative knowledge so that students can practice just their newly learned and fluent facts and therefore helps build confidence.	Controlled response times Personalised learning path Includes educator components
Number Worlds (Griffin, 2004)	Pre-K to 8th grade	Focuses on teaching mathematical concepts	Interactive teacher-led group instructional programme aims to engage students in mathematical thinking by helping them develop an understanding of the meaning behind quantities. Tasks involve interactive games such as building blocks activities and strategic digital modelling as well as digital game boards for group interaction.	Individualised approach Adresses changes in working memory by offering ample practice opportunities Weekly planner

Accelerated Math (FASTT Math, n.d.)	Grades 1 to 12	Magnitude comparison and estimation tasks Automaticity of fact retrieval Multidigit computation	Daily progress-monitoring software tool that can be used in conjunction with any core curriculum. It allows teachers to differentiate instructions based on student's needs. Based on an initial diagnostic assessment the software generates learning objectives specifically aimed at the student's needs. Based on personalised objectives the programme then generates individualized paper-and-pencil worksheet of practice problems which once completed and scanned and scored by the programme.	Personalized pacing Goal setting feature Immediate feedback
Tom's rescue (de Castro, Bissaco, Panccioni, Rodrigues & Domingues, 2014)		Arithmetical operations, number sequences, visual reasoning, geometric shapes	Uses a virtual environment in 18 computer games which aim to confront children with fun situational problems in order to stimulating reasoning in children and generating positive attitudes towards mathematics. All games are developed based on a storyline in order to promote child interaction whilst also addressing specific cognitive skills such as working memory and spatial reasoning	Use of virtual environment Playful setting

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