Half a century of study to understand dyscalculia and its research trends

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Abstract: Although dyscalculia has an estimated prevalence of approximately 5% among the school population, it remains a little-known disorder socially, having received much less attention than other learning difficulties or disorders. This research shows the results of a rigorous systematic review process carried out on a selection of relevant documents in the field of dyscalculia from Web of Science and Scopus published between 1970 and 2020, including both publications in English and Spanish. Considering the topic addressed, the results indicate that the diagnostic approach and its instrumentalization is the most dominant, followed by the study of neurological alterations, the characterization of dyscalculia symptomatology, comorbidity with other disorders, studies oriented to processes and protocols of intervention, proposals for the classification of different types of dyscalculia and, finally, research on the relationship between math anxiety and dyscalculia. Thus, it is concluded that, although there have been notable and numerous advances in the diagnosis of dyscalculia, incorporating more and better detection techniques and instruments, such growth and progress does not seem to be observed in relation to the contribution of evidence from the research for the development of interventions, mainly educational, in children with dyscalculia, as well as for the measurement of their impact.

Keyword: Dyscalculia

Medio siglo de estudios para comprender la discalculia y sus tendencias de investigación

Resumen: A pesar de que la discalculia tiene una prevalencia estimada de aproximadamente un 5% entre la población escolar, sigue siendo un trastorno poco conocido socialmente, habiendo recibido mucha menos atención que otras dificultades de aprendizaje o trastornos. Esta investigación muestra los resultados de un riguroso proceso de revisión sistemática llevado a cabo sobre una selección de documentos relevantes en el ámbito de la discalculia procedentes de Web of Science y Scopus publicados entre 1970 y 2020, incluyendo tanto publicaciones en inglés como en español. Atendiendo a la temática abordada los resultados indican que el enfoque diagnóstico y su instrumentalización es la más dominante, seguida por el estudio de alteraciones neurológicas, la caracterización de sintomatología propia de la discalculia, la comorbilidad con otros trastornos, estudios orientados a procesos y protocolos de intervención, propuestas de clasificación de diferentes tipos de discalculia y, finalmente, investigaciones sobre relaciones entre ansiedad matemática y discalculia. Así, se concluye que, si bien se han producido notables y numerosos avances en el diagnóstico de la discalculia, incorporando más y mejores técnicas e instrumentos de detección, no parece observarse un crecimiento y avance tal en relación con el aporte de evidencias procedentes de la investigación para el desarrollo de intervenciones, principalmente educativas, en niños con discalculia, así como para la medición de su impacto.

Palabra clave: Discalculia

Introduction

Nowadays modern societies require citizens to develop a set of essential numerical skills to achieve full integration in daily life. In this demanding context those who have had difficulties in learning mathematics during their schooling and have not managed to develop a reasonable level of mathematical competence are in an unfavourable situation compared to their peers. These difficulties may affect their access to the labour market and, in general, their personal and professional relationships. Currently, the Spanish education system is facing high levels of school dropout and failure in Spain (Instituto Nacional de Estadística, 2021) and students with difficulties in mathematics contribute to these figures. In fact, the results in the area of mathematics in external standardised tests such as those that form part of the Trends in International Mathematics and Science Study (TIMSS) or those of the Programme for International Student Assessment (PISA), whose reports traditionally place Spain significantly below the average of the participating countries or, where appropriate, the OECD countries, are quite worrying and can be significantly improved. In order to improve the performance of students with learning difficulties in mathematics and, more specifically, of students with specific learning disorders in mathematics such as dyscalculia, it is necessary to facilitate their full inclusion in the mathematics classroom by removing the barriers to learning that they may face through personalised designs that can cater for their individual differences and potentialities. Trillo and Trillo (2020) consider necessary to develop inclusive educational models in the classroom through the presence of children with special educational needs in the regular classroom, their participation in it and their progress. In this line, the United Nations Educational, Scientific and Cultural Organisation (UNESCO, 2021) points out as a challenge towards 2050, the collective work to govern education guided by an ethic of inclusion and based on the principles of an inclusive educational design.

The concept of mathematical learning difficulties (MLD) is generally applied to students who are below the average of their group, as well as to students whose mathematical performance is below their own average performance (Fernández-Baroja et al., 1991). MLD can be classified according to the degree of severity as mild, moderate and severe. Within the most severe group are children with dyscalculia, who are two or more standard deviations below the normative average (Abraldes et al., 2017).

Dyscalculia has an estimated prevalence between 2.27% and 6.4% of the scholastic population (Estévez et al., 2008) and its research began in the 1970s with the coining of the term by Kosc (1974). Despite this, there is a much smaller volume of scientific literature on dyscalculia than that observed in relation to other learning difficulties or disorders, such as dyslexia or Attention Deficit Hyperactivity Disorder (ADHD) (Torresi, 2018). This fact, in turn, finds its social reflection in the apparent unawareness that citizens show about this disorder (Arroyo, 2018; Kunwar & Sharma, 2020). Motivated by this situation, the aim of the present research was to characterise the main features of the most influential literature on dyscalculia through a rigorous systematic review process. In this regard, there are already reviews such as Benedicto-López and Rodríguez-Cuadrado (2019), Da Cruz-Santos and Gonçalves-Pereira (2015), Fernandes et al. (2018), Guedes et al. (2019), Haberstroh and Schulte-Körne (2019), Kranz and Healy (2012) and Oneto et al. (2012), although the one presented here takes a different approach, addressing a very broad time period (1970-2020) and focusing on research that, according to criteria that will be presented later, can be considered the most influential or have the greatest impact on the scientific community.

Theoretical framework

Dyscalculia

Dyscalculia is a specific learning disorder that affects the correct acquisition of arithmetic skills and significantly interferes with academic performance and progress, or activities of daily life related to mathematics or requiring the use of mathematics. It is an "unexpected" difficulty, since it occurs in children with normal intelligence levels and appropriate scholastic development (Sans et al., 2012). To date, the exact causes of dyscalculia are not known. The lack of available evidence means that no firm conclusions have yet been drawn about the etiology of this disorder (Mendoza-Macías, 2020). Instead, ongoing research has revealed a consensus on the multifactorial origin of dyscalculia (Kaufmann & von Aster, 2012; von Aster & Shalev, 2007). This disorder has a neurobiological origin, as alterations in various brain areas produce different deficits in mathematical skills (Butterworth et al., 2011) and probably also a genetic origin, as some researchers have found that children who have relatives with dyscalculia have a higher risk of suffering from this disorder (Junquero, 2019). It is also suggested that dyscalculia may be caused by environmental factors, such as alcohol intake during pregnancy or low birth weight, which modify and affect the functioning of mathematical skills (Gallego, 2015).

Dyscalculia is not a uniform disorder and rarely presents as a pure disorder. Variations among individuals with dyscalculia can be shown depending on the type of arithmetic difficulties they present and their greater or lesser severity and associated disorders (Rosselli & Matute, 2011). However, in general, children with dyscalculia experience difficulties in the most basic aspects of numerical processing and calculation. Thus, they may manifest poor number sense, problems in identifying, counting, writing, reading or sorting numbers, and difficulties in carrying out arithmetic operations or solving mathematical problems (Fonseca et al., 2019). Although it may present as a single disorder, it frequently coexists (approximately one quarter) with other disorders such as ADHD, dyslexia, language disorder, anxiety, etc. In addition, it is important to note that the specific terminology used throughout history has changed and varied widely. In the studies that have been considered in the process of conducting this research, different denominations have been used such as developmental dyscalculia, mathematical disabilities, arithmetic learning disabilities, mathematics disorder, ..., although all the terms seem to describe the same condition, the existence of a severe disability in the learning of mathematics.

Systematic literature review

There are several types of literature reviews: narrative, overview, integrative, conceptual analysis, systematic, systematised, review of reviews and realist (Guirao, 2015). In this research we have chosen to conduct a systematic literature review. Systematic reviews are a type of scientific research that aims to objectively and systematically integrate the results of existing studies on a given research problem, in order to establish the state of the art in that field of study. On the other hand, as can be deduced from their name, systematic reviews aim to find out "the whole truth", gathering all the available quality evidence on a specific issue (Calvache, 2019; Gisbert & Bonfill, 2004; Sánchez-Meca, 2010). The researcher needs to be aware of the studies that have been done before and the weaknesses and strengths of the literature in order to carry out meaningful research. Systematic reviews also make it possible to discover important variables that are relevant to the subject studied, synthesise, and adopt new perspectives, establish the context of the problem or identify the research methodologies and techniques used, among other contributions (Boote & Beile, 2005).

In relation to the type of systematic review, the present review is qualitative in nature, as the evidence on the literature on dyscalculia is presented in a descriptive way and no statistical analysis or meta-analysis is carried out (Aguilera-Eguía, 2014; Beltrán & Óscar, 2005).

Methodological process

This systematic review has been carried out by adopting the phases proposed by García-Peñalvo (2017) in the protocol he proposes for carrying out this type of review and following the PRISMA 2020 guidelines (Page et al., 2021). The steps followed and mentioned above are set out in detail below.

Formulation of the objective

The aim of this review is to characterise the main features of the most influential literature on dyscalculia from 1970 to the date on which the scientific literature search for this review was conducted (16 November 2022).

Selection of databases

The databases used to obtain the review documentation were Web of Science (WoS) and Scopus, as they cover the literature of almost any discipline and are the largest and most important databases worldwide (Pérez-Escoda, 2017).

Definition of inclusion and exclusion criteria

The criteria applied for inclusion and exclusion were the following:

- Documents with a publication date between 1970 and 2020 have been included. The 1970s was a time of important educational changes worldwide and, in particular, in 1974 the term dyscalculia was coined for the first time (Kosc, 1974).
- WoS database includes documents belonging to the citation indexes Social Sciences Citation Index (SSCI), Conference Proceedings Citation Index - Social Sciences and Humanities (CPCI-SSH) and Book Citation Index - Social Sciences and Humanities (BCI-SSH). The aim is to eliminate research in the field of health from the search. It has not been possible to implement this limitation in Scopus as this option is not provided.
- English and Spanish documents have been included.
- Only publications of a scientific nature have been included and not those with a merely informative or divulgative nature.
- Studies where dyscalculia is only mentioned as a symptom of a disease have been excluded, e.g. in a case study of Alzheimer's or dementia.
- Documents that had fewer than 20 citations in the two databases consulted at the time of the search have been excluded. Studies with more than 20 citations can be considered influential within the scientific domain dealing with dyscalculia since, as Bauer et al. (2016) point out, highly cited papers clearly show high interest in the scientific community.
- Studies involving adults were excluded, including those with school-age participants in the sample.

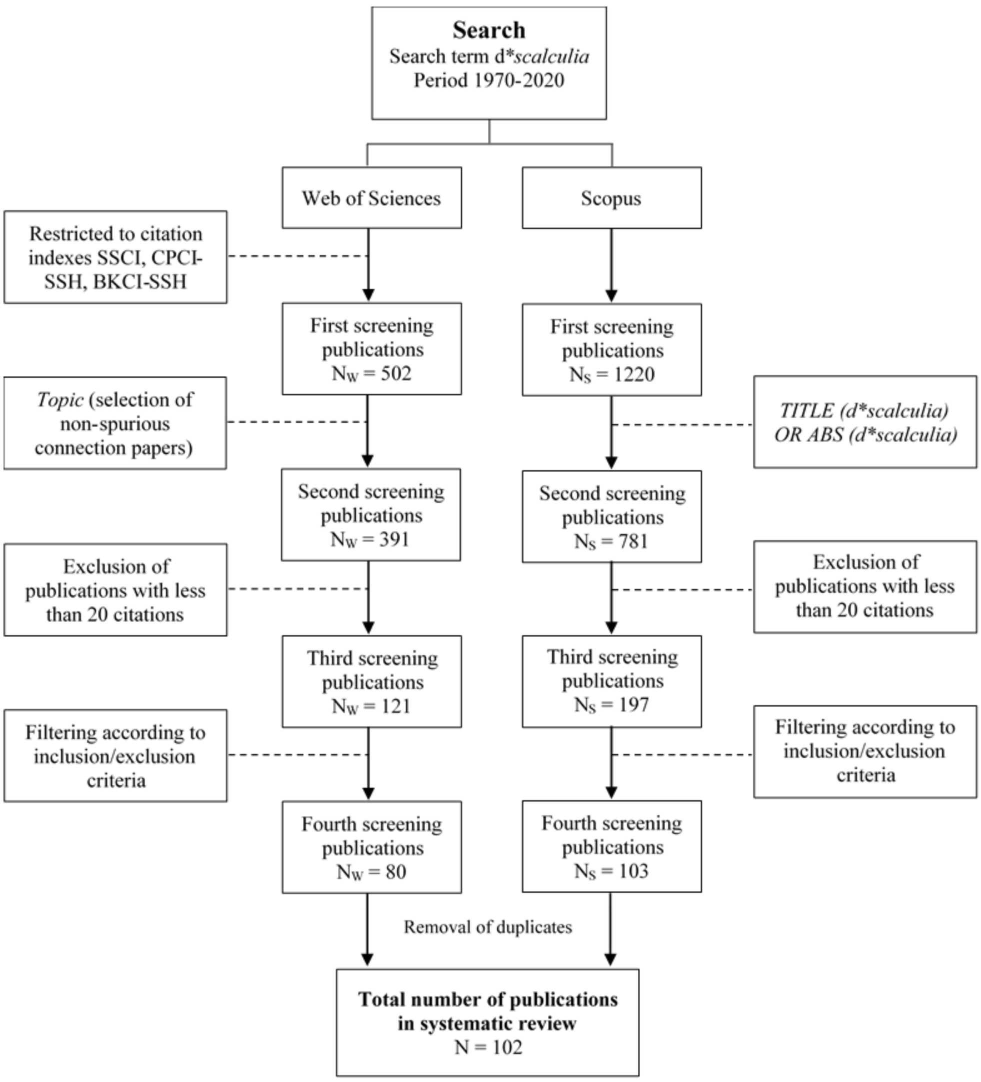
Definition of search and query terms

In both WoS and Scopus, the descriptor entered was the term d*scalculia, with the temporal limitation of 1970 to 2020 in both databases and the limitation of citation indexes related to the Social Sciences in WoS. In turn, after verifying that some of the publications selected did not deal with dyscalculia or did not really address it, the search for the term was limited to the title and abstract. Thus, in Scopus the search parameter was TITLE (d*scalculia) OR ABS (d*scalculia) while in WoS, after choosing the search field Topic (title, abstract, author keywords and keywords Plus), the publications meeting these criteria were selected manually.

Review process

The publications included in the systematic review have been screened four times. In the first screening, 502 documents were obtained in WoS and 1220 in Scopus, which were reduced to 391 in WoS and 781 in Scopus as a result of a second screening in which, as specified above, the appearance of the word dyscalculia was limited to the title and abstract of the publication. In the third screening, documents with fewer than 20 citations in both databases were excluded, resulting in 121 documents in WoS and 197 in Scopus. Limiting the number of citations to 20 is closely related to achieving the objective of the review. In order to discover the main features of the most influential literature on dyscalculia, this choice of documents has been carried out in the sense that Beaulieu (2015) points out. Finally, a fourth screening was carried out, in which the abstracts of all the publications were read and those that did not meet the established inclusion and exclusion criteria were eliminated, leaving 80 documents in WoS and 103 in Scopus. The documents were then compared between the two databases and it was observed that most of them were the same. After eliminating duplicate publications, the review finally consisted of 102 publications. A summary of the entire selection process can be seen in the diagram in Figure 1.

Figure 1.
Flowchart for the selection of targeted publications.



Data extraction

Once the studies meeting the established inclusion and exclusion criteria have been selected, the criteria by which the characteristics of the studies have been coded were made explicit:

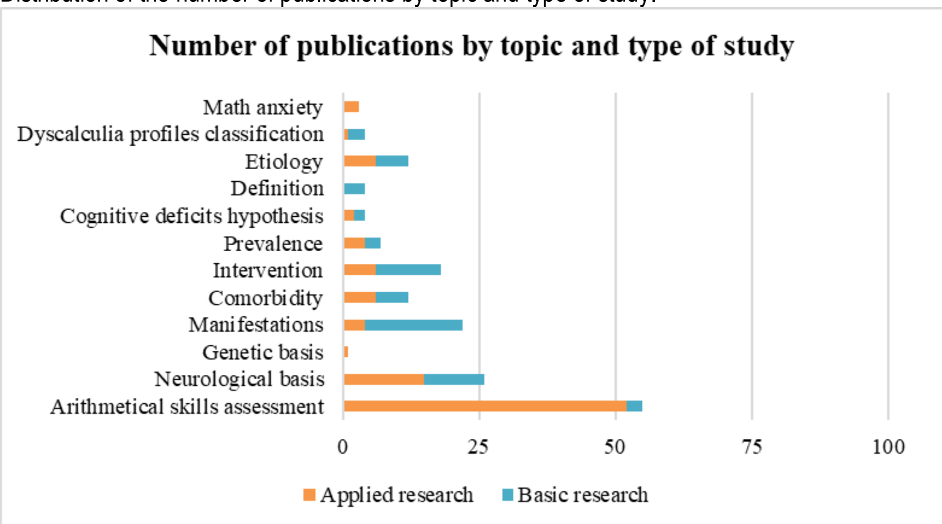
- Number of citations. The publications are ordered from the highest to the lowest number of citations, specifying the database from which these data have been obtained.
- Bibliographic reference.
- Topic.
- Type of research. The differentiation made by Esteban-Nieto (2018) on the types of research based on their purpose has been taken as a reference. A distinction has been made between basic research, which tries to explain phenomena or situations from a theoretical perspective, and applied research, which is more empirical in nature and carries out some kind of experiment. In the latter, the characteristics of the sample are specified, and it is also indicated whether it is a longitudinal or cross-sectional study depending on the time period in which it has been carried out.
- Objective and contributions of the research.

A thorough and detailed reading of the 102 publications was then carried out and their features were coded on the basis of the criteria described above.

Results and discussion

The catalog of studies that are part of the systematic review is housed in Table 1, which can be found at the Appendix of the paper. The publications are organised according to the criteria defined above and ordered from highest to lowest number of citations in the databases consulted. The majority of the publications are, in terms of type of study, quasi-experimental quantitative research with children and theoretical reviews on the features of dyscalculia. Several groups or trends can be distinguished according to the topics developed in the research reviewed. The graph in Figure 2 shows a summary of the number of publications found according to topic and type of study.

Figure 2.
Distribution of the number of publications by topic and type of study.



Evaluative or diagnostic trend

Among the others, an evaluative or diagnostic tendency stands out, where the publications are aimed at the evaluation of the mathematical skills of students with dyscalculia. On the one hand, a distinction is made between those studies whose aim has been to assess the development of a set of mathematical skills through different arithmetic tasks. The aim of these studies is, for the most part, to find out the possible deficits that children with dyscalculia may show, as is the case, for example, of the study by Kosc (1974), which also presents a definition of the disorder, a description of its possible manifestations and a classification. The results obtained by Landerl et al. (2004) and Landerl et al. (2009) associate dyscalculia with a deficit in the representation or processing of specifically numerical information, while Landerl and Kölle (2009) do so with deficits in symbolic number processing, Cowan and Powell (2014) with deficits in both the general domain and numerical factors and Ashkenazi et al. (2013) with deficits in subitizing and estimation. A group of studies linking dyscalculia to deficits in cognitive functions is also clearly identified, e.g. Szűcs et al. (2013), who indicate mainly impairments in working memory and inhibition processes. Anobile et al. (2013), Lindsay et al. (1999) and Lindsay et al. (2001) associate this disorder with attentional deficits and Wang et al. (2012) with cognitive inhibition. Rosselli et al. (2006) and Toffalini et al. (2017) report deficits in working memory, the latter adding weakness in processing speed, while Schuchardt et al. (2008) identify deficits in visuospatial working memory and Attout and Majerus (2015) in verbal working memory.

On the other hand, there are other studies that focus on the assessment of a single skill. Thus, we find the work of Piazza et al. (2010), who assess numerical acuity, those of Bugden and Ansari (2016) and Mazzocco et al. (2011), who focus on the approximate number system (ANS), that of Wilson et al. (2006) on number sense, those of Iuculano et al. (2008), Kucian et al. (2006), Mejías et al. (2011) and Mussolin et al. (2010b) focused on numerical magnitude processing (symbolic and non-symbolic), the work by Ashkenazi et al. (2012) assessing arithmetic problem solving, that of Moeller et al. (2009) on basic numerical processing (subitizing) and the study by Rosenberg-Lee et al. (2015) focused on solving simple addition and subtraction problems. Ashkenazi et al. (2009), on the other hand, assessed the representation of two-digit numbers, Morsanyi et al. (2013) did so with transitive inference problem solving, Vicario et al. (2012) on time processing, de Visscher and Noël (2014) looked at interference sensitivity in the acquisition of arithmetic facts and Jiménez-González and García-Espinel (2002) focused on choice strategies when children solve mathematical problems.

In most of the aforementioned studies, the results always show a worse performance of students with dyscalculia compared to their typically developing peers, thus allowing partially to differentiate between children with and without dyscalculia. In the particular case of Skagerlund and Träff (2016), children with dyscalculia are not compared to children in control groups (without dyscalculia), but the sample consists of children with different profiles of mathematical deficits (arithmetic fact dyscalculia and general dyscalculia). The findings provide evidence that the origins of dyscalculia in these children diverge, those with general dyscalculia present an impairment in the ANS and those with arithmetic facts suffer from an access deficit.

In other research, the assessment is carried out through computer programmes composed of a set of digital mathematical activities, such as those of Kucian et al. (2011a) using the Rescue Calcularis programme and Wilson et al. (2006) using The Number Race programme.

The assessment carried out can be extended over time, as in the longitudinal studies by Geary et al. (2000), Landerl (2013), Mazzocco et al. (2013) and Shalev et al. (1998, 2005). The research by Geary et al. (2000) concludes that in a sample of primary school children with and without learning disabilities (including dyscalculia), they show differences by displaying specific patterns of cognitive deficits. Shalev et al. (1998) identify as factors contributing to the persistence of dyscalculia the severity of the arithmetic disorder of the children in the sample and the arithmetic problems of their siblings. Landerl (2013) and Mazzocco et al. (2013) compare children with dyscalculia to their typically developing peers from 2nd to 4th grades at primary schools and from 4th grade at primary schools to 2nd year of ESO, respectively. Landerl's (2013) findings indicate that children with dyscalculia show less efficient numerical processing with prolonged response times and those of Mazzocco et al. (2013) indicate that children with dyscalculia have difficulties with fractions that persist until 2nd grade of secondary school, manifesting failures even with the easiest fractions. The last of the longitudinal studies mentioned (Shalev et al., 2005) identifies lower IQ, inattention and difficulties in writing as factors affecting the prognosis of dyscalculia.

Research by Auerbach et al. (2008) and Shalev et al. (1995) do not focus on assessing mathematical performance, as has been the case in the studies mentioned above, but rather examines the behavioural characteristics of children with dyscalculia. Their results show that these children demonstrate more behavioural problems than typically developing children and have significantly more externalising and attention problems.

Regarding the operational diagnosis of dyscalculia, there are several instruments with different characteristics. Thus, we find, for example, the work of Koumoula et al. (2004) showing the validation and standardisation of a diagnostic instrument for developmental dyscalculia in Greek population. McCloskey et al. (1991) describes a particular approach to cognitive assessment to determine the specific nature of patients with numerical processing or calculation deficits. Van Viersen et al. (2013) find that eye-tracking data from number line estimation tasks can be a useful tool for discriminating between children with and without dyscalculia. Jaekel and Wolke (2014) conclude that the risk of general cognitive and mathematical impairment increases with lower gestational age, but preterm children do not have an increased risk of dyscalculia. And Shalev et al. (2001) determine with their results that children whose relatives have dyscalculia have a 5 to 10 times higher risk of suffering from dyscalculia than the general population.

Within this evaluative or diagnostic trend, there is a group of publications that aim to determine the prevalence of dyscalculia. The results of Gross-Tsur et al. (1996) report that the prevalence of dyscalculia is 6.5%, Reigosa-Crespo et al. (2011) 3.4% without detecting gender differences, Devine et al. (2013) 5.3% without detecting such differences either and Mogasale et al. (2012) 10.5%. The review developed by Shalev et al. (2000) of studies on the prevalence of dyscalculia carried out up to 2000 shows a prevalence of between 3 and 6%.

Neurological trend

In the development of the systematic review, a second trend related to the investigation of the neurological alterations involved in dyscalculia has been discovered. On the one hand, different reviews are presented on studies whose findings present evidence of dysfunction of multiple brain areas in children with dyscalculia (Fias et al., 2013; Kaufmann, 2008; Kaufmann et al., 2011; Menon, 2016). On the other hand, empirical research shows, through magnetic resonance imaging, different findings about the brain regions that are affected in children with this disorder. Different mathematical aspects are assessed such as basic numerical processing (Price et al., 2007), exact and approximate mathematical calculation and comparison of magnitudes (Kucian et al., 2006), non-symbolic numerical magnitude processing (Kaufmann et al., 2009), arithmetic problem solving, (Ashkenazi et al., 2012; Rosenberg-Lee et al., 2015), symbolic numerical processing (Mussolin et al., 2010a), numerical representation (Simms et al., 2015), time processing (Vicario et al., 2012), spatial working memory processes (Rotzer et al., 2009) or non-symbolic distance effects (Kucian et al., 2011b). The results of these investigations show impairments in parietal, temporal and frontal brain regions and contribute to the characterization of the etiology of dyscalculia. In the same line, Jolles et al. (2016) reveal robust aberrations in the neural network and not only a dysfunction in the intraparietal sulcus. Dehaene et al. (2004) point out that disorganisation of quantity-related brain regions can create lifelong impairments in arithmetic development. And Rotzer et al. (2008) and Rykhlevskaia et al. (2009) research results indicate that children with dyscalculia manifest reduced grey and white matter volume in several brain areas while Kucian et al. (2014) suggest a possible disconnection between the fibres of both matters.

A set of publications can be identified (Bugden & Ansari, 2016; Noël & Rousselle, 2011; Skagerlund & Träff, 2014) as linked to the different hypotheses on the cognitive deficits of dyscalculia, including the access deficit hypothesis and the defective ANS hypothesis.

Theoretical trend

A third dominant group of publications presents a theoretical tendency in which the associated papers offer a review of the most important evidence or findings on dyscalculia in relation to: definition, neurological basis, the most significant cognitive deficits of this disorder, manifestations or symptoms, prevalence, comorbidity with other learning disorders or difficulties, diagnosis and intervention. These publications include Ardila and Rosselli (2002), Butterworth (2010), Butterworth et al. (2011), Butterworth and Laurillard (2010), de Smedt et al. (2013), Kaufmann et al. (2011), Kaufmann and von Aster (2012), Kucian and von Aster (2015), Rubinsten and Henik (2009), Shalev (2004), Shalev and Gross-Tsur (2001), Szűcs and Goswami (2013) and von Aster (1994). These works review dyscalculia from multiple disciplines, such as Medicine, Psychology, Neuroscience or Education and present different theoretical approaches. Other publications such as Butterworth (2005a) and Butterworth (2005b) explain the structure of cognitive number processing mechanisms in normal and abnormal development and McCloskey (1992) and McCloskey et al. (1985) do so by proposing neuropsychological and cognitive research in dyscalculia as evidence. Finally, within this group, von Aster and Shalev (2007) offer a four-stage theoretical model that serves to predict the possible neuropsychological dysfunctions of dyscalculia, Temple (1991) describes two different cases of dyscalculia through which she concludes that there are individual differences in the developmental pathways for the adult calculation system, Chodura et al. (2015) conduct a meta-analysis of the effectiveness of interventions for children with mathematical difficulties and Mazzocco and Räsänen (2013) review the main contributions that longitudinal studies have made to efforts to define dyscalculia.

Comorbidity trend

A trend has been perceived in the publications focused on the comorbidity of dyscalculia with other disorders or learning difficulties. Shalev et al. (2000) state that dyscalculia can occur with other disorders, such as ADHD, developmental language disorder or Fragile X syndrome. Rubinsten (2009) proposes some hypotheses regarding behavioural, cognitive and biological factors in cases of pure and comorbid developmental disorders, including dyscalculia. Works by Geary and Hoard (2001), Landerl et al. (2009), Maehler and Schuchardt (2016) and Willburger et al. (2008) make comparisons between children with dyscalculia and dyslexia. The latter concludes that the cognitive bases of dyslexia and dyscalculia are independent of each other while Geary and Hoard (2001) indicate that there are similarities in the deficits associated with these disorders. Landerl et al. (2009), in their study with children aged 8-10, propose that dyslexia and dyscalculia have separate cognitive profiles: dyslexia has a phonological deficit and dyscalculia a deficit in the numerical module. Maehler and Schuchardt (2016) also point out the difference in their profiles, but with a focus on working memory and adding children with ADHD to their sample. The results reveal that dyslexia corresponds to deficits in the phonological loop, dyscalculia to visuospatial deficits and ADHD to deficits in central performance. On the other hand, Karande et al. (2007) document the clinical profile and academic history of children with specific learning disabilities and co-occurrence with ADHD.

Intervention trend

There is also a trend in which publications are aimed at treatment or intervention in dyscalculia. On the one hand, there is research that carries out intervention programmes with children suffering from dyscalculia. In some of them, the intervention is carried out using diverse technological resources such as software, virtual environments or applications, and the aim is to evaluate the effectiveness and efficiency of the intervention programme. In the results of Wilson et al. (2006) it is concluded that the intervention programme with The Number Race software has increased the number sense of children with dyscalculia during the short period of time of the study. In Kucian et al. (2011a), the computer-based training programme Rescue Calcularis has produced an improvement in the mental number line representation of children with dyscalculia and the modulation of neural activation, both of which facilitate the processing of numerical tasks. In relation to this same computer programme, Käser et al. (2013) present the design and a first pilot evaluation of the training programme, and their results show that, in general, children with dyscalculia have benefited significantly from training in number representation and arithmetic operations. Castro et al. (2014) show the effectiveness of a virtual environment composed of 18 computer games covering mathematical topics in a playful environment. In other studies, the intervention is carried out through a programme made up of activities in which technological resources are not used and, as in the previous studies, the aim is to evaluate the effectiveness and efficiency of the programme. In Kaufmann et al. (2003) the results point to beneficial effects of a numeracy intervention programme that has been specifically designed to train numerical and arithmetic problem areas. The importance of basic numerical and conceptual knowledge for the successful acquisition of numeracy skills is also corroborated in this study. And Shalev and Gross-Tsur (1993) examined a group of seven children with dyscalculia who had not progressed academically despite intervention and suggested that the indications for medical or neurological assessment should be expanded.

On the other hand, there are publications that provide reviews of interventions for dyscalculia. Butterworth and Laurillard (2010) provide some ways to strengthen number sense using learning technologies. De Smedt et al. (2013) present a review of studies that provide cognitive interventions focused on number magnitude processing and point out that board and computer games are useful to foster this skill. Kaufmann (2008) argues that the use of fingers could be an important and complementary aid (to more traditional pedagogical methods) to establish mental number representations or to facilitate learning to count and calculate in children with and without dyscalculia. And Chodura et al. (2015) conducted a meta-analysis of the effectiveness of studies that have carried out interventions for children at risk of dyscalculia, concluding that the interventions were effective on average.

Classification trend

There is also a trend towards the classification of dyscalculia. Studies have investigated the different subtypes of dyscalculia that may occur among children with dyscalculia. Von Aster (2000) has identified three subtypes (verbal, arabic and pervasive subtype), Kosc (1974) six (verbal, lexical, graphic, operative, practognostic and ideognostic dyscalculia) and Kaufmann et al. (2013) differentiate between primary and secondary dyscalculia. Finally, Ramaa and Gowramma (2002) identify three groups of dyscalculia according to their comorbidity with other problems (dyscalculia without reading and writing problems, dyscalculia with writing problems and dyscalculia with both problems).

Affective trend

Finally, an affective trend has been identified, in which all publications have mathematical anxiety as a central issue. Rubinsten and Tannock (2010) investigate the effects of math anxiety on the numerical processing of children with dyscalculia, showing that for this group of children arithmetic facts and mathematics-related words are linked to negative emotions. Mammarella et al. (2015), in their findings, show that children with dyscalculia and math anxiety had difficulties with verbal memory tasks. And Devine et al. (2018) study the comorbidity of dyscalculia and math anxiety and find that children with dyscalculia were twice as likely to have high math anxiety as children without dyscalculia.

Conclusion

The interest of a systematic review is to provide extensive information on research on a topic of interest. In this document we offer the most relevant research papers published in the last thirty years related to dyscalculia in the non-adult stage.

Despite the existence of other systematic reviews, as mentioned before, in this case we provide a study over a long period of years, from a few years before the term dyscalculia was coined (Kosc, 1974) to the last few years of the great influx of scientific papers on the subject.

On the other hand, the uniqueness of the work is also due to the relevance of the studies considered. In particular, the criterion that has filtered by the number of citations ensures that the papers that have been selected are of high relevance (Bauer et al., 2016).

Therefore, the review presented here can be a useful tool to create a robust state of the art on dyscalculia in order to stimulate or encourage further research. We believe that the need for this systematic review focuses on the possession, by future researchers or anyone who is interested in learning about this disorder from the beginning, of a study that facilitates their knowledge of the most influential literature on dyscalculia, saving the time that would be spent in his search. In addition, their categorizing by topics or trends provides a better understanding and an easier access to the existing theoretical framework.

The results of the review have shown that the most influential studies on dyscalculia have been those that have carried out an assessment of the mathematical skills of children with this disorder and those that have investigated the neurological alterations involved. Different techniques and instruments have been used in the investigations, and when stating the deficits presented by these children and the brain areas affected, their conclusions have been diverse. This leads us to confirm the great heterogeneity that exists among children suffering from dyscalculia and, therefore, the need to adapt interventions to the specific needs and profiles of each of them. This heterogeneity can also be seen in the abundance of research that has studied the comorbidity of dyscalculia with other learning difficulties or disorders. It is not surprising that the third group of publications that predominate are articles offering theoretical reviews on the most relevant features of dyscalculia, as they are some of the researches that serve as a theoretical foundation for the rest of the studies (on dyscalculia assessment, classification, treatment, ...).

We consider that the aim of the research has been achieved and it has provided an overview of the characteristics of the most influential scientific activity in dyscalculia. As a limitation or weakness we can point out that the bibliographic search has been restricted to two databases which, although we believe that their potential has been well justified to provide consistent results suitable for this research, it is no less true that in the field of research in Social Sciences and, in particular, in Education, their trajectory is even less consolidated than in other fields of knowledge such as, for example, those of the Experimental Sciences. Therefore, the risk of not including publications that could have been equally relevant for the purpose of this study is a factor to be taken into account.

In conclusion, although the diagnosis of dyscalculia has evolved considerably, incorporating more and better detection techniques and instruments, there is still a need for more evidence from research on intervention processes for children with dyscalculia in terms of effectiveness and impact. In this sense, although there have been many advances in the design of digital programmes that motivate students, few interventions are carried out under an inclusive approach, and treatment is almost always carried out individually and in isolation, without considering the presence and participation of the student in the regular classroom.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report.

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Appendix

Table 1. Systematic review publications

	Number of citations	Bibliographic reference	Topic	Type of research	Objective (O) and main contributions (C)
1	WoS 491 Scopus 547	Landerl *et al.* (2004)	- Assessment of arithmetic skills - Comorbidity	Cross-cutting applied research. Sample: 8-9-year-old children with dyslexia, dyscalculia and both disorders.	O: Assess basic numerical processing tasks. C: Dyscalculia can best be defined as a deficit in the representation or processing of specifically numerical information, rather than the consequence of deficits in other cognitive abilities.
2	WoS 452 Scopus 415	Dehaene *et al.* (2004)	Neurological basis	Basic research	O: Present different findings in cognitive neuroscience on arithmetic development in the brain. C: Quantity-related brain regions disorganisation can create lifelong impairments in arithmetic development.
3	WoS 442 Scopus 421	McCloskey (1992)	Manifestations	Basic research	O & C: Discuss neuropsychological and cognitive research on dyscalculia as evidence to explain the structure of cognitive number processing mechanisms.
4	WoS 386 Scopus 433	Piazza *et al.* (2010)	Assessment of arithmetic skills	Cross-cutting applied research. Sample: preschool children, primary school children and typically developing adults and children with dyscalculia.	O: Assess numerical acuity. C: Results show a clear association between dyscalculia and impaired number sense.

	Number of citations	Bibliographic reference	Topic	Type of research	Objective (O) and main contributions (C)
5	WoS 379 Scopus 399	McCloskey *et al.* (1985)	Manifestations	Basic research	O & C: Propose a model to explain the development of numerical processing and calculation based on research evidence in dyscalculia.
6	WoS 334 Scopus 365	Butterworth (2005b)	Manifestations	Basic research	O: Present the progression of normal and abnormal development of arithmetic skills based on research in dyscalculia. C: Impaired ability to learn arithmetic, dyscalculia, can in many cases be interpreted as a deficit in the child's concept of numerosity.
7	Scopus 324	De Smedt *et al.* (2013)	- Manifestations - Neurological basis - Intervention	Basic research	O: Provide a review of numerical development, neurological basis and interventions in dyscalculia. C: Children with dyscalculia show significant deficits in their ability to compare symbolic numbers and board and computer games are useful in fostering this skill.
8	WoS 282 Scopus 322	Butterworth *et al.* (2011)	- Neurological basis - Intervention	Basic research	O: Present the neurological deficits associated with dyscalculia and examples of its intervention. C: Dyscalculia is characterised by a central deficit in the understanding of sets and their numerosities, fundamental to the understanding of other aspects of mathematics. These deficits need to be considered in the development of personalised interventions.

	Number of citations	Bibliographic reference	Topic	Type of research	Objective (O) and main contributions (C)
9	WoS 284 Scopus 303	Mazzocco *et al.* (2011)	Assessment of arithmetic skills	Longitudinal applied research. Sample: 14-year-old children with and without dyscalculia.	O: Assess approximate number system (ANS) acuity. C: Acuity on the ANS distinguishes children with mathematics learning difficulties from their peers without it, including children with low, typical or high mathematics achievement.
10	Scopus 248	Price *et al.* (2007)	Neurological basis	Cross-cutting applied research. Sample: children with and without dyscalculia.	O: Investigate the neural correlates of basic numerical processing in children with dyscalculia. C: Dyscalculia is caused by an ontogenetic disruption of the neural circuitry that supports the fundamental representation of numerical magnitude.
11	WoS 214 Scopus 248	Von Aster and Shalev (2007)	Manifestations	Basic research	O & C: Provide a four-stage model to predict possible neuropsychological dysfunctions in dyscalculia.
12	WoS 210 Scopus 248	Gross-Tsur *et al.* (1996)	- Prevalence - Comorbidity	Cross-cutting applied research. Sample: 11-year-old children with dyscalculia.	O: Determine the demographic characteristics and prevalence of dyscalculia in municipal schools in Israel. C: Results show that the prevalence of dyscalculia is 6.5% (similar to dyslexia and ADHD), affects both sexes equally and 46% have relatives with learning difficulties.

	Number of citations	Bibliographic reference	Topic	Type of research	Objective (O) and main contributions (C)
13	Scopus 219	Wilson *et al.* (2006)	- Intervention. - Assessment of arithmetic skills	Cross-cutting applied research. Sample: children aged 7-10 years with persistent and/or severe difficulties in mathematics.	O: Present the results of the initial evaluation of *The Number Race* software. C: The intervention programme with this software has increased the number sense of children with dyscalculia during the short period of the study.
14	WoS 197 Scopus 209	Butterworth (2010)	- Manifestations - Neurological basis - Intervention	Basic research	O: Describe different arithmetic processing skills affected in dyscalculia, their neural basis and examples of interventions. C: Evidence on ANS and the small number system is not sufficient to support the development of arithmetic skills. There is a need to collect data from longitudinal and intervention studies to understand the developmental trajectories of students with and without dyscalculia.
15	WoS 33 Scopus 205	Kucian *et al.* (2011a)	- Intervention - Assessment of arithmetic skills - Neurological basis	Cross-cutting applied research. Sample: 9-year-old children with and without dyscalculia.	O: Present the results of the assessment of the Rescue Calcularis programme using functional magnetic resonance imaging. C: The training programme has produced an improvement in the mental number line representation of children with dyscalculia and the modulation of neural activation, both of which facilitate the processing of numerical tasks.

	Number of citations	Bibliographic reference	Topic	Type of research	Objective (O) and main contributions (C)
16	WoS 183 Scopus 200	Landerl *et al.* (2009)	- Assessment of arithmetic skills - Comorbidity	Cross-cutting applied research. Sample: 8-10 year old children with dyscalculia and dyslexia.	O: Assess and test the phonological processing skills and arithmetic skills of children with dyscalculia or dyslexia. C: Dyslexia and dyscalculia have separate cognitive profiles. Dyslexia has a phonological deficit and dyscalculia has a deficit in the numerical module.
17	WoS 163 Scopus 174	Szűcs *et al.* (2013)	- Assessment of arithmetic skills - Manifestations	Cross-cutting applied research. Sample: 9-10 year old children with dyscalculia.	O: Assess various cognitive functions (magnitude representation, working memory, inhibition, attention and spatial processing) to test the dominant theory that assumes that dyscalculia is related to a deficit in the ANS. C: This theory is insufficient to explain dyscalculia. In this theory, problems with visuo-spatial processing and attention are related to deficits in working memory and inhibition.
18	WoS 162 Scopus 173	Iuculano *et al.* (2008)	Assessment of arithmetic skills	Cross-cutting applied research. Sample: 8-9 year old children with normal mathematical performance, low performance and dyscalculia.	O: Assess whether the arithmetic impairment is due to a deficit in the ability to represent and process exact or approximate numerosities. C: Although children with dyscalculia performed normally in all non-symbolic tasks, a significant impairment has been perceived in the symbolic tasks of comparison and addition of numbers.

	Number of citations	Bibliographic reference	Topic	Type of research	Objective (O) and main contributions (C)
19	WoS 159 Scopus 175	Mussolin *et al.* (2010b)	Assessment of arithmetic skills	Cross-cutting applied research. Sample: 10-11 year-old children with and without dyscalculia.	O: Assess a specific numerical deficit of dyscalculia, the comparison of numbers in symbolic and non-symbolic format. C: Children with dyscalculia have a deficit in the specialised cognitive system underlying the processing of numerical magnitude.
20	WoS 132 Scopus 195	Kosc (1974)	- Manifestations - Assessment of arithmetic skills	- Theoretical review. - Cross-cutting applied research. Sample: 11-year-old children.	O: Present a definition and classification of dyscalculia and assess the arithmetic skills of children with possible risk of dyscalculia. C: Dyscalculia is a structural disorder of mathematical skills whose origin lies in affections of the parts of the brain responsible for mathematical abilities.
21	Scopus 173	Butterworth (2005a)	Manifestations	Basic research	O: Review the evidence on normal and abnormal development of arithmetic skills. C: The defective numerical module hypothesis refers to selective deficits that arise when the numerical module does not develop normally.
22	Scopus 158	Kucian *et al.* (2006)	- Assessment of arithmetic skills - Neurological basis	Cross-cutting applied research. Sample: 11-year-old children with and without dyscalculia.	O: Assess the exact and approximate mathematical calculation and comparison of magnitudes, through functional magnetic resonance imaging. C: In children with dyscalculia there is evidence of impaired recruitment of neural resources when processing analogous magnitudes of numbers.

	Number of citations	Bibliographic reference	Topic	Type of research	Objective (O) and main contributions (C)
23	Scopus 157	Rotzer *et al.* (2008)	Neurological basis	Cross-cutting applied research. Sample: 9-year-old children with and without dyscalculia.	O: Look for differences between grey and white matter in the brains of children with and without dyscalculia. C: The neurological basis of impaired arithmetic processing skills may be due to decreased grey and white matter volumes in the frontoparietal network.
24	WoS 126 Scopus 148	Rubinsten and Henik (2009)	- Manifestations - Neurological basis - Comorbidity	Basic research	O & C: Present a review of the biological and cognitive findings of dyscalculia and to outline theoretical frameworks for the study of the neurocognitive basis of dyscalculia.
25	WoS 115 Scopus 122	Kaufmann *et al.* (2011)	Neurological basis	Basic research	O: Present a review of studies using functional magnetic resonance imaging to identify areas of brain activation in numerical and computational processing. C: Differences in brain activation are observed between children with and without dyscalculia in number-relevant parietal regions and in the (pre)frontal and occipital cortex.
26	WoS 114 Scopus 127	Schuchardt *et al.* (2008)	- Assessment of arithmetic skills - Comorbidity	Cross-cutting applied research. Sample: 10-year-old children with and without dyscalculia and with and without dyslexia.	O: Assess working memory functioning in children with dyscalculia and dyslexia. C: If children's phonological deficits are important precursors of dyslexia and visuo-spatial deficits of dyscalculia, this knowledge can be used for early identification of children at risk.

	Number of citations	Bibliographic reference	Topic	Type of research	Objective (O) and main contributions (C)
27	WoS 114 Scopus 136	Shalev *et al.* (2000)	- Prevalence - Comorbidity	Basic research	O: Review studies on prevalence and comorbidity of dyscalculia. C: Dyscalculia shows a prevalence of 3-6% and can occur with other disorders such as ADHD, developmental language disorder or Fragile X syndrome.
28	WoS 105 Scopus 114	Landerl and Kölle (2009)	Assessment of arithmetic skills	Cross-cutting applied research. Sample: 8, 9 and 10 year old children with dyscalculia.	O: Assess the development of numerical processing skills in children with dyscalculia. C: Children with dyscalculia are considerably slower on all symbolic number processing tasks and do not show the same level of automatic number processing as typically developing children. However, no strong evidence has been found that they process numbers qualitatively differently from typically developing children in arithmetic.
29	Scopus 136	Shalev *et al.* (2005)	Assessment of arithmetic skills	Longitudinal applied research. Sample: 11-year-old children with dyscalculia.	O: Assess factors affecting the prognosis of dyscalculia. C: Lower IQ, inattention and writing difficulties are factors associated with the persistence of dyscalculia.
30	WoS 105 Scopus 114	Geary and Hoard (2001)	- Manifestations - Comorbidity	Basic research	O: Review cognitive studies on the arithmetic competence of children with learning difficulties in mathematics. C: There are similarities in the deficits associated with dyscalculia and dyslexia.

	Number of citations	Bibliographic reference	Topic	Type of research	Objective (O) and main contributions (C)
31	WoS 102 Scopus 123	Temple (1991)	Manifestations	Basic research	O: Describe two different cases of dyscalculia, procedural and factual. C: In developmental dyscalculia there are individual differences in the developmental pathways for the adult calculation system.
32	Scopus 121	Rykhlevskaia *et al.* (2009)	- Assessment of arithmetic skills - Neurological basis	Cross-cutting applied research. Sample: 7-9 year-old children with and without dyscalculia.	O: Assess macro and micro deficits in brain structures of children with and without dyscalculia. C: Children with dyscalculia show a reduced volume of grey and white matter in several brain areas.
33	WoS 100 Scopus 108	Shalev and Gross-Tsur (2001)	Manifestations	Basic research	O: Present the clinical features, etiology, diagnosis and treatment of dyscalculia. C: Dyscalculia is a learning disability with a neurological basis and a genetic predisposition. Its diagnosis is based on the assessment of arithmetic skills and its intervention must be adapted to individual characteristics.
34	WoS 98 Scopus 120	Mussolin *et al.* (2010a)	Neurological basis	Cross-cutting applied research. Sample: 10-year-old children with and without dyscalculia.	O: Analyse the brain bases of dyscalculia related to symbolic numerical processing. C: Dyscalculia is associated with impairment in areas involved in processing numerical magnitude.

	Number of citations	Bibliographic reference	Topic	Type of research	Objective (O) and main contributions (C)
35	WoS 91 Scopus 102	Rotzer *et al.* (2009)	Neurological basis	Cross-cutting applied research. Sample: 11-12-year-old children with and without dyscalculia.	O: Compare the brain activity of spatial working memory processes in children with and without dyscalculia. C: Dyscalculia involves impaired spatial working memory processes that may inhibit the formation of spatial number representations and the storage and retrieval of arithmetic facts.
36	WoS 83 Scopus 98	Shalev *et al.* (2001)	Genetic basis	Cross-cutting applied research. Sample: 39 children with dyscalculia, 21 mothers, 22 fathers, 90 siblings and 16 second-degree relatives.	O: Determine the familial aggregation of dyscalculia. C: Approximately half of the siblings of children with dyscalculia were also dyscalculic, having 5 to 10 times the risk of dyscalculia as the general population.
37	WoS 86 Scopus 97	Noël and Rousselle (2011)	Cognitive deficits hypothesis	Basic research	O: Explain the different perspectives between the deficient ANS hypothesis and the access deficit hypothesis. C: The first deficit manifested in dyscalculia is the result of a basic dysfunction in the process of constructing the exact representation of symbolic numbers. Later on, the reduced acuity in the ANS appears.
38	WoS 78 Scopus 94	Szűcs and Goswami (2013).	- Prevalence - Cognitive perspective - Etiology - Intervention	Basic research	O & C: Present an overview of different theoretical approaches to identifying and defining developmental dyscalculia and consideration of assessment and experimental work.

	Number of citations	Bibliographic reference	Topic	Type of research	Objective (O) and main contributions (C)
39	WoS 70 Scopus 94	Shalev (2004)	- Manifestations - Prevalence - Etiology - Diagnosis - Intervention	Basic research	O & C: Describe the most characteristic features of dyscalculia (definition, etiology, prevalence, symptoms, theoretical models, diagnosis, treatment).
40	WoS 78 Scopus 93	Geary *et al.* (2000)	Assessment of arithmetic skills	Cross-cutting applied research. Sample: 84 primary school children with and without learning disabilities (mathematics, reading or both).	O: Assess longitudinally mathematical development through experimental and psychometric tasks. C: Differences have been found between groups with learning disabilities and those without, showing specific patterns of cognitive deficits.
41	WoS 75 Scopus 85	Reigosa-Crespo *et al.* (2011)	Prevalence	Cross-cutting applied research. Sample: 11652 children in grades 2-9.	O: Estimate the prevalence and gender ratio of dyscalculia in a borough in Havana. C: The prevalence of dyscalculia in the sample is 3.4% and no gender differences were found.
42	WoS 64 Scopus 78	Willburger *et al.* (2008)	Assessment of arithmetic skills	Cross-cutting applied research. Sample: 99 children aged 8-10 years with dyscalculia, dyslexia, both disorders and controls.	O: Examine naming speed in a carefully selected sample of children with dyslexia and dyscalculia. C: The cognitive bases of dyslexia and dyscalculia are independent of each other and no differential impact of special demands on inhibition and displacement of executive functions has been found for any of the four groups.

	Number of citations	Bibliographic reference	Topic	Type of research	Objective (O) and main contributions (C)
43	WoS 61 Scopus 74	Von Aster (2000)	Classification of dyscalculia profiles	Cross-cutting applied research. Sample: 93 children with low performance in mathematics between 2nd and 4th grade of primary school.	O: Investigate different subtypes of developmental dyscalculia according to various aspects of numerical skills that are defective. C: Three subtypes of dyscalculia have been detected: verbal, arabic and pervasive subtype.
44	WoS 55 Scopus 70	Kaufmann *et al.* (2013)	- Heterogeneity - Manifestations - Classification of dyscalculia profiles	Basic research	O & C: Describe the characteristics of dyscalculia that make it a heterogeneous disorder and present research challenges related to dyscalculia classification, diagnosis and research criteria.
45	Scopus 68	Ashkenazi *et al.* (2012)	- Assessment of arithmetic skills - Neurological basis	Cross-cutting applied research. Sample: 17 children aged 7-9 years with dyscalculia and 17 controls.	O: Investigate arithmetic problem solving deficits in children with dyscalculia using functional magnetic resonance imaging. C: Children with dyscalculia not only exhibit aberrant activity in key brain regions involved in mathematical cognition, but also fail to modulate task-relevant neural responses and representations of different arithmetic problems.
46	Scopus 65	Butterworth and Laurillard (2010)	- Diagnosis - Intervention	Basic research	O & C: Describe different ways of identifying dyscalculia and offer some ways to strengthen number sense using learning technologies.

	Number of citations	Bibliographic reference	Topic	Type of research	Objective (O) and main contributions (C)
47	WoS 60 Scopus 64	Anobile *et al.* (2013)	Assessment of arithmetic skills	Cross-cutting applied research. Sample: 68 typically developing children aged 8-11 years.	O: Investigate the relationship between mathematical performance, numerosity perception and sustained visual attention in school children. C: Attentional deficits, such as visual deficits, are implicated in disorders such as dyscalculia.
48	Scopus 64	Fias *et al.* (2013)	Neurological basis	Basic research	O: Highlight and describe the origin of dyscalculia through a multicomponential neurocognitive view. C: Neurocognitive theoretical frameworks in dyscalculia involving multiple functional components are needed.
49	WoS 55 Scopus 62	Rubinsten and Tannock (2010)	Math anxiety	Cross-cutting applied research. Sample: 12 children with dyscalculia and 11 typically developing children aged 7 to 13 years.	O: Investigate the effects of math anxiety on numerical processing in children with dyscalculia. C: Results show that for the group of children with dyscalculia, arithmetic facts are related to negative emotions as well as words related to mathematics.

	Number of citations	Bibliographic reference	Topic	Type of research	Objective (O) and main contributions (C)
50	WoS 57 Scopus 58	Cowan and Powell (2014)	- Assessment of arithmetic skills - Etiology	Cross-cutting applied research. Sample: 29 children with dyscalculia, 42 with underachievement and 187 with typical development.	O: Assess the contribution of general domain deficits and numerical factors to the three sample groups. C: Results show that the majority of children with dyscalculia exhibit deficits in both general domain and numerical factors.
51	WoS 54 Scopus 58	Ardila and Rosselli (2002)	- Manifestations - Neurological basis - Comorbidity - Intervention	Basic research	O & C: Review the characteristics of acalculia and dyscalculia in relation to: historical perspective, symptoms, subtypes, comorbidity, neuropsychological perspective, diagnosis and rehabilitation.
52	WoS 39 Scopus 57	Kaufmann *et al.* (2009)	- Neurological basis - Assessment of arithmetic skills	Cross-cutting applied research. Sample: 9 children with dyscalculia and 9 typically developing children from 2nd to 4th grade of primary school.	O: Investigate the neural correlates of non-symbolic numerical magnitude processing in children with and without dyscalculia. C: Findings suggest less consistent neural activity in right (intra)parietal regions when processing non-symbolic numerical magnitudes and compensatory neural activity in left (intra)parietal regions in developmental dyscalculia.

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53	WoS 51 Scopus 55	Shalev *et al.* (1998)	Assessment of arithmetic skills	Longitudinal applied research. Sample: 185 primary school children with dyscalculia.	O: Identify factors contributing to the persistence of dyscalculia. C: Results show that the factors associated with the persistence of dyscalculia are the severity of the arithmetic disorder and the arithmetic problems of the siblings of the children in the sample.
54	WoS 42 Scopus 52	Rosenberg-Lee *et al.* (2015)	- Neurological basis - Assessment of arithmetic skills	Cross-cutting applied research. Sample: 19 children with dyscalculia and 21 with typical development.	O: Examine how the brain circuits used by young children with dyscalculia to solve simple addition and subtraction problems differ from those used by typically developing children. C: The findings suggest that the intraparietal sulcus and its functional circuits are an important site of dysfunction during addition and subtraction problem solving in dyscalculia, and that inappropriate task modulation and hyperconnectivity are the underlying neural mechanisms.
55	WoS 45 Scopus 51	Kaufmann *et al.* (2003)	Intervention	Cross-cutting applied research. Sample: 6 children with dyscalculia in 3rd grade of primary school.	O: Evaluate the efficiency of a numeracy intervention programme that has been specifically designed to train numerical and arithmetic problem areas. C: Results demonstrate the beneficial effects of the intervention programme and corroborate the importance of basic numeracy and conceptual knowledge for the successful acquisition of numeracy skills.

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56	Scopus 50	Ramaa and Gowramma (2002)	Ranking	Basic research	O & C: Describe the processes adopted by two independent studies to identify and classify children with dyscalculia in primary schools.
57	WoS 41 Scopus 48	Mazzocco *et al.* (2013)	Assessment of arithmetic skills	Longitudinal applied research. Sample: 11 children with dyscalculia, 18 with underachievement and 93 with typical development.	O: Test whether knowledge of fractions differs between children with dyscalculia, low achievers and typically developing children from 4th grade of primary school to 2nd grade of secondary school. C: Children with dyscalculia have difficulties with fractions that persist until 2nd grade of secondary school, showing a failure to conceptually extract meaningful information from even the easiest fraction representations.
58	WoS 43 Scopus 47	Moeller *et al.* (2009)	Assessment of arithmetic skills	Cross-cutting applied research. Sample: two 10-year-old children with dyscalculia and 8 typically developing children.	O: Investigate the nature of the deficit in subitizing in children with dyscalculia using eye movement data. C: Results show that children with dyscalculia manifest a deficit in basic numerical processing (subitizing).

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59	WoS 42 Scopus 46	Käser *et al.* (2013)	Intervention	Cross-cutting applied research. Sample: 32 9-year-old children with dyscalculia.	O: Present the design and a first pilot evaluation of the computer-based training programme Calcularis for children with dyscalculia or difficulties in learning mathematics. C: Results show that, in general, the children have benefited significantly from training in numerical representation and arithmetic operations.
60	WoS 42 Scopus 46	Devine *et al.* (2013)	- Prevalence	Cross-cutting applied research. Sample: 1004 children aged 7-10 years.	O: Estimate the prevalence and gender ratio of United Kingdom dyscalculia using different criteria. C: The prevalence of dyscalculia in the sample is 5.3% and no gender differences were found.
61	WoS 41 Scopus 45	Simms *et al.* (2015)	- Neurological basis - Etiology	Cross-cutting applied research. Sample: 115 preterm children aged 8-10 years and a control group of 77 children.	O: Identify the nature and origin of the mathematical difficulties of premature children in comparison with children with dyscalculia. C: Results indicate that functional imagery during number representation tasks would result in different patterns of brain activation between preterm children and those with developmental dyscalculia.
62	Scopus 45	Kaufmann and von Aster (2012)	- Etiology - Comorbidity - Diagnosis - Intervention	Basic research	O & C: Review the literature related to dyscalculia from multiple disciplines: medicine, Psychology, Neuroscience and Education.

	Number of citations	Bibliographic reference	Topic	Type of research	Objective (O) and main contributions (C)
63	WoS 35 Scopus 44	Bugden and Ansari (2016)	- Cognitive deficits hypothesis - Assessment of arithmetic skills	Cross-cutting applied research. Sample: 15 children with dyscalculia and 15 typically developing children aged 11 to 13.	O: Examine whether children with persistent developmental dyscalculia have an ANS deficit. C: Results show that children with dyscalculia demonstrated inaccurate ANS acuity compared to controls. Visuospatial working memory predicts individual differences in ANS acuity.
64	WoS 39 Scopus 44	Kaufmann (2008)	- Neurological basis - Intervention	Basic research	O: Review recent research findings suggesting a neurofunctional link between the fingers and numerical processing. C: The use of fingers could 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.
65	WoS 43 Scopus 43	Shalev *et al.* (1995)	- Manifestations	Cross-cutting applied research. Sample: 140 children with dyscalculia and control group.	O: Assess the behavioural characteristics of children with dyscalculia. C: Results show that children with dyscalculia demonstrate more behavioural problems than typically developing children and have significantly more attention problems.
66	Scopus 42	Kucian and von Aster (2015)	- Neurology - Manifestations - Diagnosis - Intervention	Basic research	O & C: Review the following aspects of dyscalculia: neural and behavioural level, barriers to definition and diagnosis and intervention.

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67	WoS 37 Scopus 41	Rosselli *et al.* (2006)	Assessment of arithmetic skills	Cross-cutting applied research. Sample: 17 children with dyscalculia, 13 with reading disorders and 20 with typical development between 11 and 12 years old.	O: Examine the mathematical skills and analyse the memory skills of two groups: children with dyscalculia and children with reading disorders. C: Results indicate that children with dyscalculia and children with reading disorders show a similar pattern of mathematical impairment. Both subgroups scored significantly lower than the control group on working memory tasks.
68	WoS 36 Scopus 40	Attout and Majerus (2015)	- Assessment of arithmetic skills - Etiology	Cross-cutting applied research. Sample: 16 children with dyscalculia and 16 with typical development.	O: Explore the capacity of verbal working memory in dyscalculia by distinguishing between memory for item information (the items to be retained) and memory for order information (the order of items within a list). C: Results show that children with dyscalculia perform significantly worse than controls in the working memory order condition, but not in the item condition.
69	WoS 37 Scopus 40	Ashkenazi *et al.* (2009)	Assessment of arithmetic skills	Cross-cutting applied research. Sample: 13 children with dyscalculia and 16 controls aged 9 years.	O: Examine the representation of children with dyscalculia of two-digit numbers in comparison to typically developing children. C: Results show that children with dyscalculia show a larger distance effect than controls in two-digit number comparisons.

	Number of citations	Bibliographic reference	Topic	Type of research	Objective (O) and main contributions (C)
70	WoS 35 Scopus 39	Landerl (2013)	Assessment of arithmetic skills	Longitudinal applied research. Sample: 41 children with dyscalculia and 42 with typical development.	O: Investigate the development of numeracy skills of children with dyscalculia compared to those with typical development from 2nd grade to 4th. C: Findings indicate that children with dyscalculia show less efficient numerical processing reflected in specifically prolonged response times.
71	Scopus 39	Mogasale *et al.* (2012)	Prevalence	Cross-cutting applied research. Sample: 1134 children aged 8-11 years.	O: Measure the prevalence of specific learning disabilities (dyslexia, dyscalculia and dysgraphia) among primary school children in a city in India. C: Results show that the prevalence of dyscalculia is 10.5%.
72	WoS 27 Scopus 38	Ashkenazi *et al.* (2013)	Assessment of arithmetic skills	Cross-cutting applied research. Sample: Primary school children.	O: Examine the abilities of children with dyscalculia in two types of object enumeration tasks (subitizing and estimation). C: Results indicate that pattern recognition difficulties may play an important role in subitizing and estimation deficits among children with dyscalculia.

	Number of citations	Bibliographic reference	Topic	Type of research	Objective (O) and main contributions (C)
73	WoS 36 Scopus 37	Lindsay *et al.* (2001)	- Assessment of arithmetic skills - Etiology	Cross-cutting applied research. Sample: 27 primary school children with dyscalculia and 56 controls.	O: Determine whether students with dyscalculia have attention difficulties. C: Results show that students with arithmetic difficulties have more attentional problems than other children and students with attentional difficulties are more at risk for arithmetic difficulties.
74	WoS 29 Scopus 36	Mammarella *et al.* (2015)	Math anxiety	Cross-cutting applied research. Sample: children with dyscalculia and high math anxiety and typically developing children.	O: Examine the development of verbal and visuospatial short-term memory and working memory in children with dyscalculia and high math anxiety. C: Findings show that children with dyscalculia do not show impairments in verbal tasks but do show impairments in visuospatial tasks. Children with math anxiety had difficulties with verbal memory tasks.
75	Scopus 36	Kucian *et al.* (2011b)	- Neurological basis - Assessment of arithmetic skills	Cross-cutting applied research. Sample: 15 children with dyscalculia and 15 controls aged between 10 and 11.	O: Investigate the activation of brain areas related to non-symbolic distance effects in children with and without dyscalculia. C: Results suggest that children with dyscalculia involve areas attributed to greater difficulty in response selection than control children, possibly due to the impaired development of spatial number representation in dyscalculia.

	Number of citations	Bibliographic reference	Topic	Type of research	Objective (O) and main contributions (C)
76	Scopus 35	Kucian *et al.* (2014)	- Neurological basis - Assessment of arithmetic skills	Cross-cutting applied research. Sample: 15 children with dyscalculia and 15 10-year-old controls.	O: Investigate possible differences in white matter fibre integrity between children with dyscalculia and controls using diffusion tensor imaging. C: Results describe the deficient projection of fibres between parietal, temporal, and frontal regions in children with dyscalculia and raise the question of whether dyscalculia can be seen as a disconnection syndrome.
77	WoS 23 Scopus 34	Chodura *et al.* (2015)	Intervention	Basic research	O: Meta-analyse the effectiveness of interventions for children with mathematical difficulties. C: Interventions for children at risk of dyscalculia were effective on average. Mathematics interventions are effective for children with mathematical difficulties, although there is a large variation in effect size between studies.
78	WoS 32	Toffalini *et al.* (2017)	Assessment of arithmetic skills and intelligence	Cross-cutting applied research. Sample: 1049 children diagnosed with specific learning disabilities.	O: Analyse how the most common diagnoses of specific learning disabilities (dyscalculia, dyslexia) are characterised by different intellectual profiles. C: Results show that specific learning disability subgroups share similar weaknesses in working memory and processing speed but, are also characterised by different intellectual profiles.

	Number of citations	Bibliographic reference	Topic	Type of research	Objective (O) and main contributions (C)
79	WoS 32 Scopus 33	Skagerlund and Träff (2016)	- Assessment of arithmetic skills - Etiology	Cross-cutting applied research. Sample: 77 children with dyscalculia from 4th to 6th grade of primary school.	O: Investigate whether dyscalculia in children with different profiles of mathematical deficits (dyscalculia of arithmetic facts and general dyscalculia) has the same or different cognitive origin. C: The findings provide evidence that the origins of dyscalculia in children with different profiles diverge. Children with general dyscalculia have an impairment in the ANS and those with arithmetic facts suffer from an access deficit.
80	Scopus 33	Karande *et al.* (2007)	- Comorbidity - Assessment of arithmetic skills	Cross-cutting applied research. Sample: 50 children diagnosed with specific learning disabilities.	O & C: Document the clinical profile and academic history of children with specific learning disabilities and co-occurrence with ADHD.
81	WoS 26 Scopus 32	Koumoula *et al.* (2004)	- Evaluation of an instrument - Diagnosis	Cross-cutting applied research. Sample: 240 children aged 7-11 years.	O & C: Validate and standardise a diagnostic instrument for developmental dyscalculia in the Greek population in order to obtain relevant epidemiological data.

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82	WoS 28 Scopus 31	McCloskey *et al.* (1991)	Diagnosis	Basic research	O & C: Describe a particular approach to cognitive assessment to determine the specific nature of patients with numerical processing or calculation deficits.
83	WoS 29 Scopus 30	Morsanyi *et al.* (2013)	Assessment of arithmetic skills	Cross-cutting applied research. Sample: 13 children with dyscalculia, 16 controls and 14 with high mathematical abilities, average age 10 years.	O: Examine performance on transitive inference problems in children with dyscalculia, with typical development and with outstanding mathematical abilities. C: Results show a worse performance of children with dyscalculia, showing a relationship between mathematical skills and the ability to reason independently of one's beliefs.
84	WoS 29 Scopus 30	Mejías *et al.* (2012)	Assessment of arithmetic skills	Cross-cutting applied research. Sample: children with dyscalculia and controls.	O: Assess the numerical estimation of children with dyscalculia through symbolic and non-symbolic number comparison tasks. C: Results show a worse performance of children in numerical estimation than controls. It is proposed that this may arise from an initial mapping deficit between number symbols and magnitude representation.

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85	WoS 27 Scopus 29	Vicario *et al.* (2012)	- Assessment of arithmetic skills - Neurological basis	Cross-cutting applied research. Sample: 10 children with dyscalculia and 11 controls aged 8 years.	O: Assess the time processing skills of children with dyscalculia compared to a control group. C: Results show that the time processing deficits observed in children with dyscalculia are consistent with evidence of a shared frontoparietal neural network for representing time and quantity.
86	WoS 22 Scopus 29	Auerbach *et al.* (2008)	Manifestations	Longitudinal applied research. Sample: 58 children aged 10-11 years with persistent dyscalculia.	O: Examine behavioural problems between a group of children with persistent dyscalculia and a group of children with non-persistent dyscalculia. C: Results show significant behavioural problems in the 16-17 age group, particularly in externalising and attention problems.
87	WoS 24 Scopus 28	Menon (2016)	Neurological basis	Basic research	O & C: Review neuroimaging studies that provide evidence suggesting that visuospatial working memory is a specific source of vulnerability in children with mathematical learning disabilities and should be considered as a key component in cognitive, neurobiological and developmental models of the acquisition of typical and atypical mathematical skills.

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88	WoS 24	Jolles *et al.* (2016)	Neurological basis	Cross-cutting applied research. Sample: 19 children with dyscalculia with a mean age of 8 years.	O: Characterise the intrinsic functional connectivity of the intraparietal sulcus neuronal network in children with dyscalculia. C: Results indicate that children with dyscalculia show hyper connectivity of the intraparietal sulcus with a bilateral frontoparietal network. They are characterised by robust neural network aberrations and not only intraparietal sulcus dysfunction.
89	Scopus 28	De Castro *et al.* (2014)	Intervention	Cross-cutting applied research. Sample: 300 children aged 7-10 years.	O & C: Show the effectiveness of a virtual environment consisting of 18 computer games covering mathematical topics in a playful environment that can be run on the Internet with the possibility of player interaction via chat.
90	WoS 23 Scopus 28	Skagerlund and Träff (2014)	- Assessment of arithmetic skills - Cognitive deficits hypothesis	Cross-cutting applied research. Sample: 4th grade primary school children with dyscalculia and controls.	O: Increase understanding of the developmental trajectory of ANS and symbolic number processing skills in children with dyscalculia. C: Children with dyscalculia suffer from a general numerical processing deficit and the symbolic numerical processing deficit tends to be preceded by a deficit in the ANS.

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91	WoS 24 Scopus 28	De Visscher and Noël (2014)	Assessment of arithmetic skills	Cross-cutting applied research. Sample: 46 children in 4th grade of primary school.	O: Assess the impact of interference sensitivity on the acquisition of arithmetic facts in children with dyscalculia. C: Results show that children with low arithmetic fluency experience hypersensitivity to memory interference compared to children with typical arithmetic fluency.
92	WoS 24 Scopus 27	Van Viersen *et al.* (2013)	- Assessment of arithmetic skills - Diagnosis	Cross-cutting applied research. Sample: a 9-year-old girl with dyscalculia.	O: Test whether eye-tracking data from number line estimation tasks can be a useful tool to discriminate between children with and without dyscalculia. C: Eye-tracking data can be used to discern different number processing and estimation strategies in typically developing children and children with dyscalculia.
93	Scopus 25	Mazzocco and Räsänen (2013)	- Manifestations - Intervention	Basic research	O & C: Review the major contributions that longitudinal studies have made to recent efforts to define dyscalculia and how these contributions inform best practices for the prevention and remediation of this disorder.

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94	Scopus 24	Jiménez González and García Espinel (2002)	Assessment of arithmetic skills	Cross-cutting applied research. Sample: 148 children aged 7-9 years.	O: Examine whether there are differences between children with dyscalculia, low achievers and typically developing children in choice strategies when solving mathematical problems. C: No significant differences were found between dyscalculic and low-achieving children, both groups relied more on back-up strategies than the typically developing group. The discrepancy between IQ and performance does not seem to be a relevant criterion to differentiate between individuals with dyscalculia and low achievers in mathematics.
95	WoS 21 Scopus 24	Shalev and Gross-Tsur (1993)	Intervention	Cross-cutting applied research. Sample: 7 children in 3rd grade of Primary School.	O: Examine a group of 7 children with dyscalculia who had not progressed academically despite special education intervention. C: Suggest that the indications for medical or neurological assessment be expanded to include children who do not improve academically despite appropriate professional intervention.

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96	Scopus 23	Jaekel and Wolke (2014)	- Assessment of arithmetic skills - Etiology	Longitudinal applied research. Sample: 922 infants aged 23-41 weeks gestational age.	O: Assess whether the risk of dyscalculia in preterm infants increases with lower gestational age and whether this is associated with dyscalculia. C: The risk of general cognitive and mathematical impairment increases with lower gestational age, but preterm infants do not have an increased risk of dyscalculia.
97	Scopus 23	Maehler and Schuchardt (2016)	- Comorbidity - Assessment of arithmetic skills	Cross-cutting applied research. Sample: 31 children with dyslexia, 37 with dyslexia and ADHD, 18 with dyscalculia, 21 with dyscalculia and ADHD, 34 with ADHD and 31 controls from 2nd to 4th grade of primary school.	O: Analyse commonalities and differences in working memory in children with dyslexia and/or attention deficit disorders and with dyscalculia and/or attention deficit disorders. C: Results reveal distinct patterns of working memory deficits: dyslexia corresponds to phonological loop deficits, dyscalculia to visuospatial deficits and ADHD to central performance deficits.
98	WoS 23 Scopus 23	Lindsay *et al.* (1999)	Etiology	Basic research	O & C: Review studies addressing the impact of attentional deficits on dyscalculia.

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99	Scopus 22	Devine *et al.* (2018)	Math anxiety	Cross-cutting applied research. Sample: 1757 children in primary school (8-9 years) and secondary school (12-13 years).	O: Investigate the comorbidity of developmental dyscalculia and math anxiety. C: Results show that children with developmental dyscalculia were twice as likely to have high math anxiety as children with typical maths performance. However, 77% of children with high math anxiety had typical or high mathematics performance.
100	Scopus 21	Wang *et al.* (2012)	Assessment of arithmetic skills	Cross-cutting applied research. Sample: 45 children with dyscalculia, 45 with dyslexia and 45 controls aged 10-11 years.	O: Present a comparison of the cognitive inhibition skills of children with dyslexia, dyscalculia and control. C: Results suggest the complexity of cognitive inhibition skills developed by the three groups of students, despite some regular patterns.
101	WoS 20 Scopus 20	Rubinsten (2009)	- Etiology - Comorbidity	Basic research	O & C: Examine how specific cognitive functions promote dyscalculia and to propose some hypotheses regarding behavioural, cognitive, and biological factors in cases of pure and comorbid developmental disorders.
102	Scopus 20	Von Aster (1994)	- Manifestations - Neurological basis - Etiology	Basic research	O & C: Conduct a literature review on the concepts related to arithmetic disorders through a neuropsychological approach.

Note. Publications are ordered from highest to lowest number of citations.