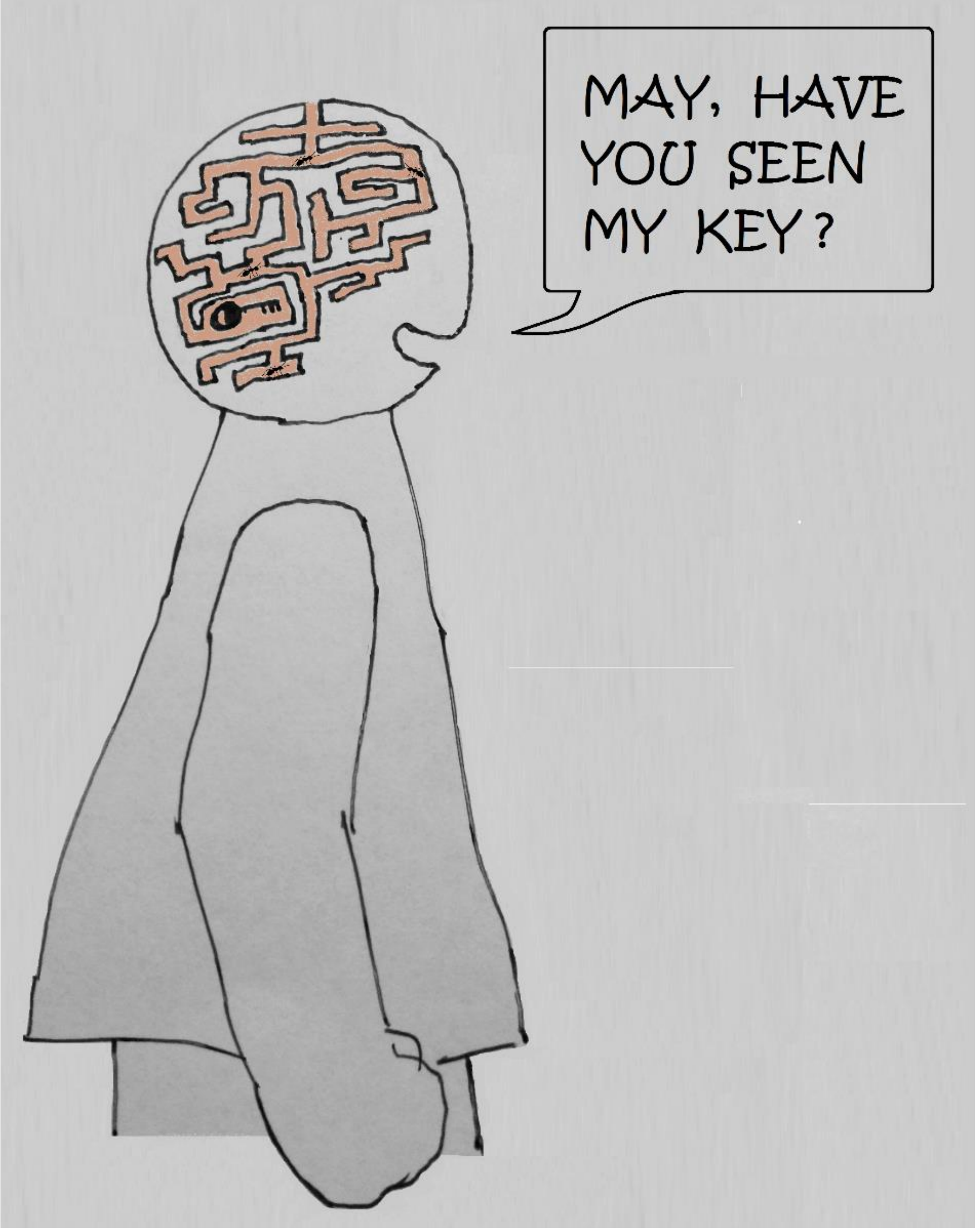
Abstract

Mathematical skills are essential for a person's development, their ability to function and make daily decisions. Poor numeracy skills severely impact all aspects of a person's life, including financial planning, time management, work opportunities - even cooking for one's family. Dyscalculia is a specific mathematical learning disorder affecting the individual's ability to learn and process numerical information, which leads to severe difficulties in learning mathematics. Research on dyscalculia lags behind dyslexia, but recently, the field of cognitive neuroscience has shown interest in this mathematical learning disorder. In this thesis, I investigate what current cognitive neuroscientific research has to say about dyscalculia, and how interventions may affect how children with dyscalculia learn. In order to investigate this, I conducted a a systematic literature review. Systematic reviews are a type of document analysis that utilize strict inclusion and exclusion criteria and systematic methods to identify and analyze texts. To identify relevant texts, I used the internet search engines *Web of Science, PubMed, ERIC* and *PsycNET* to search for keywords related to dyscalculia and cognitive neuroscience. Seventeen articles were identified, including four review articles and 13 research articles utilizing brain-imaging technology. Cognitive neuroscientific research indicated that children with dyscalculia show deficits in numerical processing. FMRI has identified increased brain activation patterns in children's frontal lobes, indicating strong demands on compensatory cognitive processing mechanisms. Major conflicts were identified between research communities, particularly regarding the definition of dyscalculia as a heterogeneous or homogeneous disability. These conflicts hinder the advancement of knowledge on dyscalculia. The articles addressed similar educational perspectives to explain the numerical difficulties experienced by children with dyscalculia, including deficits in magnitude representation and in accessing the meanings of numerical symbols. In addition, neurocognitive research confirmed existing behavioral research describing dyscalculic children's poor choice of problem-solving strategies. Interventions presented by the articles included adaptive computer software and intensive, individual tutoring sessions. The articles also reported results from fMRI sessions suggesting that appropriate interventions can help to remediate aberrant brain activity in children with dyscalculia.


MAY, HAVE YOU SEEN MY KEY?

Preface

The fields of medicine and psychology have always fascinated me, particularly when it comes to the brain. How do our brains work? How do we learn and grow? What is intelligence? And what happens when things go wrong?

As young children learn, their brain cells create pathways to each other, trillions of times over. Some connections are established and strengthened, while others waste away – it seems random, like a colony of ants digging tunnels - but it isn't random. Our brains are surprisingly similar to each other's, and they even show similarities to the brains of other species. Scientists have even found that we use similar brain areas as monkeys to process some types of information!

So it isn't very surprising that I decided to write my master's thesis on the educational aspect of neuroscience. As a teacher, I love to show my students how amazing our universe is, and how exciting it is to know that we never run out of new things to learn. Considering these interests, choosing to study the neuroscience behind learning disorders and learning about how children with mathematics disabilities can be helped – it was a fairly simple choice to make and a project which I thoroughly enjoyed.

Many people helped me a great deal throughout the process of writing this thesis and I am very thankful. I am particularly indebted to my advisor, Nina Volckmar, who was of great help in organizing this paper, and in helping me stay focused – when everything was so fascinating to read and write about!

I would also like to thank Hanna Kvello and Gisle Marhaug, who helped me organize and prioritize my time, stay on task, and most of all, just believed in me – their support was invaluable and I cannot thank them enough.

I am also indebted to friends and family, both here in Norway and in the United States – whether they were sharing encouraging words, or, like Tony and Sherri, reading through parts of this paper and pointing out that I was doing perfectly well on my own.

Lastly, I do not have enough words with which to thank my wonderful woman, May-Britt. She is the kindest person I know - she never gives up on me, brings me food, gives me hugs and encouragement, helps me be a little more organized and searches for the things I have lost... again. I'm lucky to be with someone who is as curious and interested in the world as I am – every day is a gift. Thank you ♥

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1 Introduction

Governments, professionals and researchers from all over the world seem to be in agreement about the importance of mathematics in modern society. Mathematical skills are essential for a person's development, ability to function and make daily decisions. People use mathematics to manage their finances and go shopping, when they plan their time, and even when they cook meals for their family. Mathematical knowledge assists us in making sound decisions and in understanding the world around us. In addition, mathematics is necessary for learning and for students to have access to higher education, whereas a lack of mathematical skills significantly impacts a person's employability and limits his or her career opportunities. In fact, Parsons and Bynner (2005) demonstrate that poor numeracy skills affect an individual's quality of life to a greater extent than poor reading skills alone. They found this to be particularly true for women with poor mathematical skills: they are more likely to live in a non-working household and feel like they lack control over their lives.

Nonetheless, mathematical ability continues to be considered secondary to literacy skills, and research on mathematical instruction is significantly less common. This can easily be evidenced by a simple literature search using the academic search engine *Web of Science*[1]. A quick search for "reading" and "instruction" resulted in 9,332 published articles; whereas an identical search for "mathematics" and "instruction" resulted in 3,602 published articles[2].

Likewise, the difference in the amount of research on the reading disability "dyslexia" compared to the research on the mathematics disability "dyscalculia" is vast. A *Web of Science* search resulted in 11,914 articles about dyslexia, while only 1,206 articles[3] about dyscalculia were identified. This lack of scientific research has greatly diminished the quality of knowledge that exists on dyscalculia, both among educators and among the research community. As a result, the literature on dyscalculia is fragmented, with researchers holding a multitude of opinions regarding dyscalculia's definitions, causes and characteristics. In fact, some educators don't even recognize dyscalculia as a legitimate learning disability. This lack of cohesion and uniformity within the research and education communities has resulted in numerous perspectives, diagnostic criteria and educational approaches for remediation, many

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[1] https://www.webofknowledge.com/

[2] *Web of Science* search undertaken 13.07.2017 comparing "reading" or "mathematics" and "instruction" texts.

[3] *Web of Science* search undertaken 13.07.2017 comparing "dyslexia or reading disability/difficulty" and "dyscalculia, mathematical learning disability/difficulty, Mathematical disability/difficulty, Arithmetic Learning disorder/disability/, or Arithmetic disability/difficulty"

of which may not be effective. The result of this is that some children with this learning disorder do not receive the help that they need.

One new approach for identifying and helping children with learning problems is emerging in the field of cognitive neuroscience. Cognitive neuroscience is concerned with investigating the areas of the brain that control our higher cognitive processes like thinking and learning. In controlled research studies, scientists identify and compare different regions of the brain that are stimulated when test subjects engage in specific thoughts or actions. One recent area of research within the field of cognitive neuroscience involves the study of the areas of the brain associated with mathematical development. Some researchers have even started trying to identify possible effects that various educational methods or treatment approaches may have on the brains of children with and without mathematical learning difficulties. Many educational professionals hope that this knowledge can be used to identify effective educational approaches to help prevent and remedy students' learning difficulties.

However, because cognitive neuroscience is such a new field, and because neuroscience is generally considered to be outside most people's understanding, educators and school professionals do not have a good source of information about the neuroscience behind learning. Flobakk's 2015 doctoral thesis illustrates many of the misconceptions that the public has about the functioning of the human brain and "brain-training". Schools and educators commonly share these beliefs and often utilize teaching methods that adhere to these misconceptions. In addition, some schools and families invest in "brain-training" products that promise to improve children's knowledge and skills. Unfortunately, neurological research shows that many of these "brain-myths" are incorrect and that these products offer little educational value. Valuable time and money is wasted. This lack of knowledge is also apparent in pedagogical research in the sense that there is little communication between the two fields, and educational researchers do not, as a rule, utilize knowledge from the field of neuroscience.

The purpose of this thesis is to review and analyze recent scientific literature about cognitive neuroscience and dyscalculia in an attempt to bridge some areas of these two fields. My research aim includes one primary and one follow-up secondary question:

1.) *What does recent research on cognitive neuroscience have to say about dyscalculia?*
2.) *What does neurological research on dyscalculia say about the effect of interventions on children's learning?*

One could answer these questions by doing a literature review, choosing some articles that seem relevant, and reading and commenting on them[4]. This may result in an informative, well-thought out thesis. However, doing so would not result in a *representative* picture of recent scientific literature. Also, a researcher that does not use a scientific method for selecting the articles that are included in a literature review can easily show selection bias by choosing articles that adhere to his or her own hypothesis or perspective. My goal for this thesis was to produce a *representative* review of recent cognitive neuroscientific research on dyscalculia to investigate current findings within this field. In order to do this, and to answer my two research questions, I conducted a systematic review, using a strict and structured methodology, to try to identify important contributions and gaps in the existing scientific literature. Professional literature was located using the internet search engines *Web of Science, PubMed*[5]*, ERIC*[6] and *PsycNET*[7]*,* and inclusion and exclusion criteria was applied in order to identify *all* relevant articles. I then compared these articles, observed patterns, and analyzed my findings in light of recent pedagogical theory on dyscalculia and mathematical development. By investigating current research on dyscalculia and interventions for helping children with this mathematical learning disability, I have attempted to connect the fields of cognitive neuroscience and educational research.

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[4] Östergren (2013) did exactly this in his doctoral thesis on mathematical learning disabilities.

[5] *https://www.ncbi.nlm.nih.gov/pubmed/*

[6] https://eric.ed.gov/

[7] *psycnet.apa.org/*

2 Method

In this chapter, I will explain what a systematic literature review is and the method for carrying out a systematic review. I will then present my research methodology and the criteria I used to identify the articles that compose my data set. This will be followed by the theoretical chapter, laying the groundwork for the data analysis that follows.

Thagaard (2013) pointed out that researchers carrying out qualitative research often switch between inductive and deductive research designs. For example, a researcher may utilize theory to interpret data (taking a deductive approach), and use the data to develop ideas or new theoretical perspectives (an inductive approach). In this research project, I began with an explorative literature search based on some background theoretical knowledge and a general research question: *What does cognitive neuroscientific research have to say about mathematical learning disorders?* I used this question to survey the literature base to find out about what types of scientific research were available, and which technical terms researchers currently use. I began with this survey because the research combination of cognitive neuroscience and dyscalculia is a new area of study, and I did not know how many, or what kinds of articles I would find.

I utilized this inductive approach to help me narrow down the focus for this thesis, to identify the relevant theoretical perspectives, and to design and carry out my literature review. However, I simultaneously employed a deductive approach, because these theoretical perspectives helped to further refine the criteria used to filter the many articles identified in the literature searches. This interplay between theory and research design, and inductive and deductive approaches has been evident throughout the process of writing this thesis, although the overall approach has been inductive, or what Gough, Oliver, and Thomas (2012) referred to as a “configurative review”.

Systematic Literature Reviews

A systematic review is “a research article that identifies relevant studies, appraises their quality and summarizes the results using a scientific methodology” (Khan, Kunz, Kleijnen, & Antes, 2011, p.1). Jesson, et al. (2011, p. 12) described a systematic literature review as having “a clear stated purpose, a question, a defined search approach, stating inclusion and exclusion criteria, producing a qualitative appraisal of articles.” According to Jesson, et al. (2011, p.12), a systematic review is undertaken through six essential steps:

1. Design the research question.

2. Design the plan.
3. Search for literature.
4. Apply exclusion and inclusion criteria.
5. Apply quality assessment.
6. Synthesis.

Methodological design for this systematic literature review

I applied the approach of Jesson, Matheson, and Lacey (2011) in an attempt to answer my two research questions: “What does recent research on cognitive neuroscience have to say about dyscalculia?” and “What does neurological research on dyscalculia say about the effect of interventions on children’s learning?” In order to answer these questions, I conducted a methodical literature search, utilizing key words and electronic databases, as well as the use of strict inclusion and exclusion criteria, to identify relevant scientific literature. However, because the literature on dyscalculia is fragmented and includes numerous terms and explanations for this disability, I had to use a combination of keywords. Possible keywords related to dyscalculia include “mathematical learning difficulties”, “mathematical learning disorder”, “specific mathematical learning disabilities”, “mathematics disability”, “dyscalculia”, “developmental dyscalculia”, “acalculia”, “arithmetic learning disorder/difficulty” and “arithmetic disorder”. The search engines *Web of Science, PubMed, ERIC* and *PsycNET* were utilized to locate scientific literature using these keywords. These search engines are a valuable tool in conducting a systematic literature review because they, unlike *Google Scholar*[8], include easily accessible options for filtering search results, such as filtering by year, language, type of text, quality and so forth. Using clear inclusion and exclusion criteria allow for a more precise, objective and methodical literature search, and assisted with insuring the transparency in my methods, as well as reducing the volume of texts that had to be sorted through.

In order to identify which keywords I would use in my literature search, I first surveyed the research databases to find out which terms are synonymous with dyscalculia and have been used in educational research. Table 1 lists all of the words with which I began my survey. At first, I included mathematical terms related to educational research on dyscalculia because I did not know how many articles on just cognitive neuroscience and dyscalculia would be found.

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[8] https://scholar.google.no/

Table 1. Original list of possible search words. Only words highlighted in gray received hits in the four database searches and were included in the search analysis.

Acalculia	Mathematical	Numeracy
Arithmetic	Mathematical deficit	Numerical
Arithmetic difficulty	Mathematical difficulty	Numerical magnitude
Arithmetic disability	Mathematical disability	Numerical magnitude processing
Arithmetic disorder	Mathematical disorder	Numerical representation
Arithmetic learning deficit	Mathematical learning deficit	Specific mathematical disability
Arithmetic learning difficulty	Mathematical learning difficulty	Specific mathematical disorder
Arithmetic learning disability	Mathematical learning disability	Specific mathematical learning disability
Arithmetic learning disorder	Mathematical learning disorder	Specific mathematical learning disorder
Developmental dyscalculia	Mathematical learning dysfunction	
Dyscalculia	Mathematics	

This initial database survey resulted in nineteen search terms which received hits using the four search engines. I then combined these nineteen identified search terms with keywords relating to the field of neuroscience, including: “cognitive neuroscience”, “educational neuroscience”, “brain research”, “brain imaging”, and “fMRI”[9]. By surveying which keywords were used in research articles, I was able to identify the most relevant keywords for my literature search, which made it easier to filter through the articles in a methodical way. Table 2 shows the possible search combinations that were utilized and lists how many hits were received for each search, using the four internet search engines.

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[9] Functional Magnetic Resonance Imaging (fMRI)

Table 2. Keyword combinations and their combined search results using the four search engines. Words highlighted in gray were identified as synonyms for dyscalculia and were included in the final search list.

Search words	Cognitive Neuroscience	Educational Neuroscience	Brain Imaging	Brain Research	fMRI	Total hits
Acalculia	28	1	19	9	113	170
Arithmetic	745	22	198	203	1021	2189
Arithmetic difficulty	1	0	0	0	0	1
Arithmetic learning disorder	1	0	0	0	0	1
Developmental dyscalculia	71	9	26	13	129	248
Dyscalculia	126	18	122	18	238	522
Mathematical	3151	31	1957	1349	16310	22798
Mathematical difficulty	4	1	0	0	1	6
Mathematical disability	2	0	0	2	9	13
Mathematical Learning difficulty	2	0	0	1	0	3
Mathematical Learning disability	12	0	0	0	10	22
Mathematics	1318	38	435	704	5010	7505
Numeracy	70	4	3	8	16	101
Numerical	1524	24	1083	1109	3328	7068
Numerical Magnitude	92	3	22	19	142	278
Numerical Magnitude Processing	13	0	8	1	37	59
Numerical Representation	68	1	9	9	40	127
Specific Mathematical disability	3	0	0	0	0	3
Total hits	7231	152	3882	3445	26404	41114

I chose to exclude the search words related to mathematics and mathematical concepts, because these search combinations identified far too many articles, most of which were not *directly* related to dyscalculia. The search words highlighted in gray were identified as keywords synonymous with dyscalculia that also received hits in combination with the search terms related to cognitive neuroscience. I left out “Developmental Dyscalculia” as a search term because the keyword phrase “dyscalculia” would identify the same articles, making the additional keyword unnecessary. I excluded “acalculia” because it refers to an acquired mathematical disorder that is due to brain injury or illness, and is not synonymous with dyscalculia, which is a brain-based *developmental* disability.

My final search keywords related to dyscalculia were: “dyscalculia”, “mathematical difficulty”, “arithmetic difficulty”, “arithmetic learning disorder”, “mathematical learning difficulty”, “mathematical disability”, “mathematical learning disability” and “specific mathematical disability". The asterisk key was used (e.g. mathematical difficulty*) to indicate to the search engine that I wanted to include all the different forms of the nouns in my keyword searches, eliminating additional searches for plural forms of the keywords. These eight keywords were then combined with the search terms "cognitive neuroscience", "educational neuroscience", "brain imaging", "brain research", and "fMRI" to identify all relevant articles that related to both research areas. These searches[10] were carried out using each of the four search engines, and all results were documented.

After I located all available neuroscientific articles, I applied exclusion and inclusion criteria, and assessed the quality of each article (steps 4 and 5 from Jesson, et al., 2011), in order to identify only the articles that related directly to my research questions.

The following lists the criteria I used to sort my results and identify relevant scientific literature:

Inclusion criteria:
- literature about neuroscience and dyscalculia, including:
    - research studies using fMRI or other brain-scanning methods
    - literature with a clear focus on both cognitive neuroscience and dyscalculia
- literature that discusses numerical processing (numerical representation, numerical magnitude or the manipulation of numerals)
- literature discussing research that uses children as research subjects
- peer-reviewed articles published in professional journals
- literature written in English
- literature from the last 10 years

Exclusion criteria:
- literature discussing general mathematical difficulties that does not have a clear focus on dyscalculia and the numerical processing factors involved
- literature focused heavily on one side of the topic, including:
    - behavioral/pedagogical research where neurocognitive research is not thoroughly documented or a main focus
    - neurological research centered on brain-scanning methods or technology where dyscalculia is not the main focus
- literature about adults with dyscalculia
- literature focusing on domain-general factors of learning, such as information processing,

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[10] The specific search phrase was (dyscalculia OR "mathematical difficulty*" OR "arithmetic difficulty*" OR "arithmetic learning disorder*" OR "mathematical learning difficulty*" OR "mathematical disability*" OR "mathematical learning disability*" OR "specific mathematical disability") AND ("cognitive neuroscience" OR "educational neuroscience" OR "brain imaging" OR "brain research" OR fMRI)

working memory or attention
- literature investigating other learning disorders or learning problems not directly related to mathematics, including reading and phonological skills
- literature about math anxiety or emotional/social aspects of mathematical learning
- literature about mathematical spatial ability or rotation skills
- literature about time, measurement or geometry (e.g. mathematical topics that involve other aspects of mathematics than numbers and magnitude), or more advanced mathematics like algebra or calculus
- literature about acalculia, a mathematical disability normally caused by brain injury or medical-related factors
- literature about cognitive neuroscience and developmental disorders (e.g. Autism spectrum disorders) or chromosomal syndromes (e.g. William's syndrome, Down's syndrome, Turner's syndrome)

Research centered on the relationship between mathematical learning difficulties and domain-general factors of learning, language and/or phonological skills was excluded because, while these factors contribute to general mathematical learning problems, research has not identified these areas as being central causes or contributing factors *specifically* related to dyscalculia. In addition, literature on adults with dyscalculia was excluded as neurological research has identified significant differences between how adults and children process mathematical information, leading researchers to conclude that research using adults does not reflect children's mathematical development. No neurocognitive research on dyscalculia used children as test subjects prior to 2006, and so literature prior to this has also been excluded.

All articles were peer-reviewed and received a quality factor ranking of 1 or 2 from *Scimago Journal Rankings*[11] or from *Web of Science* with the exception of one article. Quality factor rankings describe how many professional articles have cited literature from the journal in question (Guerrero-Bote & Moya-Anegón, 2012). Q1 indicates the highest quality journals (or those that are statistically most influential), whereas a Q4 ranking refers to a lower quality (or less-well known journal for that year). The one exception was Kucian et al. (2006), which was published in the journal "Behavioral and Brain Functions" (BBF). For 2006, the first year that BBF was published, the journal received a quality factor ranking of Q3. However, since then, BBF has typically received a Q2 ranking. I chose to include Kucian et al. (2006) because it is a landmark article – the first time fMRI research was published about children with dyscalculia, and Kucian et al. (2006) is an article that is repeatedly referred to in the majority of the articles in this thesis.

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[11] (SCImago, 2007)

According to Jesson et al. (2011), the sixth step in writing a systematic literature review is to synthesize the data. In order to do this, I first tabulated all of the articles, making notes in the tables about the article types, research populations used, the definitions and perspectives held by the researchers, and the researchers' methods, experimental results and conclusions. Khan et al. (2011) writes that tabulating data aids interpretation and improves transparency. Tabulating this information helped a great deal, because it allowed me to compare and find patterns within the corpus, and because the articles varied in many different respects (e.g., different article types, different perspectives, different definitions and research populations), so a traditional meta-analysis was not possible and a descriptive approach was required instead.

3 Theory

Before I present the results of my data collection and synthesis, I will first present relevant educational theories on dyscalculia, as well as pertinent aspects of cognitive neuroscience. This information will be presented to facilitate a focused and theoretically-grounded discussion of my results, and to answer my research questions. I begin the chapter by defining and characterizing dyscalculia. Then, I present cognitive theories explaining how mathematical thinking develops in children with and without dyscalculia. After that, I explain some of the arithmetic and problem-solving difficulties that children with dyscalculia face. In the second part of this chapter, a brief presentation of cognitive neuroscience will be given, followed by a short explanation of pertinent neuroscientific research methods and perspectives.

Dyscalculia: definition and characteristics

Difficulties in learning mathematics are common, and are varied in type and severity. Most researchers[12] estimate that approximately 3-7% of all children have a mathematical learning disability. This is comparable to the percentage of children with dyslexia: approximately one child in every classroom struggles with mathematics enough to be diagnosed as having a mathematical learning disorder. And yet there is no consensus among researchers or practitioners regarding a uniform term for mathematical learning disability: neither is there a uniform definition or explanation on which diagnostic materials can be developed. Instead, the technical terms used, as well as the characteristics of a mathematical learning disability vary from researcher to researcher. Some alternative terms that researchers use include: “mathematical learning difficulty”, “specific mathematical learning disability”, “dyscalculia”, “acalculia”, “arithmetic learning disorder” and even “general mathematical difficulties”.

The World Health Organization (2016, p.194) referred to a “Specific disorder of arithmetical skills” and defines it as a

> specific impairment in arithmetical skills that is not solely explicable on the basis of general mental retardation or of inadequate schooling. The deficit concerns mastery of basic computational skills of addition, subtraction, multiplication, and division rather than of the more abstract mathematical skills…

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[12] 3-6% (Kucian, Grond, et al., 2011; Kucian et al., 2006; Kucian & von Aster, 2015; Mussolin et al., 2010; Price, Holloway, Rasanen, Vesterinen, & Ansari, 2007; Rotzer et al., 2007; Rubinsten & Henik, 2009), 3.6-6.5% (Butterworth, 2005), 5-6% (Shalev & Shalev, 2004), 7% (D. C. Geary, 2010), 5-8% (D. C. Geary & Hoard, 2005)

The World Health Organization also specified that this disorder is developmental, not due to brain lesions or brain damage, and is not associated with a reading or spelling disorder.

Shalev and Shalev (2004) p.766) defined “Developmental dyscalculia” (DD) as a “specific learning disability affecting the normal acquisition of arithmetic skills in spite of normal intelligence, emotional stability, scholastic opportunity, and motivation.” Shalev and Shalev suggested that dyscalculia be diagnosed when there is at least a two-year discrepancy between a child’s chronological grade in school and his or her mathematical skills involving number concepts, number facts and/or arithmetic procedures. However, the authors also pointed out that mathematical disabilities can have numerous contributing factors and that all academic abilities, psychological and emotional aspects should undergo a detailed assessment.

Kaufmann et al. (2013, p.4) explained that developmental dyscalculia is a mathematical learning disorder that has its roots in a deficit of numerical abilities, and referred to two types:

> Primary DD is a heterogeneous disorder resulting from individual deficits in numerical or arithmetic functioning at behavioral, cognitive/neuropsychological and neuronal levels. The term secondary DD should be used if numerical/arithmetic dysfunctions are entirely caused by non-numerical impairments (e.g., attention disorders).

Geary and Hoard (2005) used the term “Mathematical Learning Disability” (MLD) to categorize children that score in the lowest 25% on a standardized mathematics test for more than one consecutive year. Geary and Hoard further described three subtypes of MLDs: a procedural subtype (children that struggle primarily with arithmetic procedures), a semantic memory subtype (children that struggle with retrieving number facts), and a visuospatial subtype (children that struggle with the spatial representation of numerical and mathematical information). However, the notion that there are different types of mathematical learning disabilities is controversial and, at this point, most researchers do not support subtypes of dyscalculia. In addition, while many researchers maintain that children with dyscalculia are a heterogeneous group with many different strengths and weaknesses, the vast majority of researchers agree that the *fundamental* deficit of dyscalculia pertains to problems with understanding, processing and acquiring *numerical* information and knowledge.

According to the Department for Education and Skills, children with dyscalculia lack an intuitive grasp of numbers and have difficulty understanding simple number concepts and comparing numbers (DfES, 2001). Dyscalculic children also have problems with learning and remembering number facts and procedures, and in performing accurate and fluent calculations. Even when children with dyscalculia are able to produce a correct answer, their answers are presented with a lack of confidence. Children with dyscalculia rely on either rote learning or inflexible calculation procedures that are immature and ineffective compared to the procedures chosen by their peers. In addition, procedures are often carried out mechanically or automatically, and without an understanding of the concept behind them (Bugden & Ansari, 2015; DfES, 2001; Ostad, 2010; Reeve & Gray, 2015).

In this thesis, I have chosen to use the term dyscalculia, as used by researchers[13] such as Butterworth (2005); DfES (2001); Kaufmann, Vogel, Starke, Kremser, Schocke, et al. (2009); Kucian and von Aster (2015); Mussolin et al. (2010); Price et al. (2007); Rotzer et al. (2007); Rubinsten and Henik (2009), and Shalev and Shalev (2004), to emphasize the focus of a numerical explanation of this learning disorder. By using the term "dyscalculia" instead of "mathematical learning disability" or "mathematical learning difficulties" (general or specific), I point out that, while there can be many types, causes and characteristics of mathematical disabilities, "developmental dyscalculia" denotes a specific – and often more severe – mathematical disability affecting a child's representation, acquisition, and use of numerical concepts, symbols and procedures.

Most researchers do acknowledge that factors such as attention difficulties, as well as problems with working memory, executive functioning, information processing and visual-spatial abilities can exacerbate, or be exacerbated by dyscalculia. These factors are known as domain-general factors, or factors that generally impact learning, but are not specific to any one area, or domain, of learning. Language and reading abilities can also affect mathematical performance, because mathematics involves speaking, listening, reading, vocabulary, and word processing and usage. However, language and mathematics are distinct learning domains, and although comorbidity is common, difficulties with speaking, reading or spelling are not *specifically* associated with dyscalculia any more than problems with numerical processing are related to dyslexia (Butterworth 2005). In addition, factors such as socio-economic status, environment, emotional issues, problematic behavior and poor instruction can all aggravate or lead to problems in learning mathematics. However, the majority of researchers agree that dyscalculia, a *specific* mathematical learning disability, is not *caused* by these domain-general, language, emotional or social factors. (Bugden & Ansari, 2015; Butterworth & Yeo, 2004; Kaufmann et al., 2013; Reeve & Gray, 2015; Regiosa-Crespo &

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[13] Some authors refer to dyscalculia as "developmental dyscalculia". However, since dyscalculia is, by definition, a developmental disability, I decided that the term "dyscalculia" was sufficient.

Castro, 2015). Instead, dyscalculia is understood to be a neurodevelopmental disorder rooted in specific numerical deficits that involve the understanding, accessibility and use of numerical information – although genetics and early experiences may play partial roles. These numerical deficits are explained in the next section.

Dyscalculia: cognitive mechanisms behind numerical difficulties

Multiple theories exist to explain numerical development, including the “Approximate Number System” (ANS) and the “Numerosity Coding Hypothesis” (NCH). The ANS and NCH models describe children’s innate ability to understand and compare numerical magnitudes. Numerical magnitude refers to the cardinal aspect of numbers: the understanding that the last number counted in a set denotes the quantity of that set, or its numerical magnitude. The child’s understanding of the relationships between different magnitudes and sets forms the foundation for his or her understanding of the number concept and further arithmetic development. Deficits in these numerical magnitude systems may cause a series of mathematical difficulties thought to underlie dyscalculia. However, other researchers have argued that dyscalculia is not caused by a deficit in comparing magnitudes, but rather in accessing the meaning of numeric symbols – this is referred to as the “Access Deficit Hypothesis” (ADH). In this subchapter, these models will be presented and used to explain the cognitive deficits underlying dyscalculic children’s numerical difficulties.

In Butterworth (2005), the author proposed that dyscalculic children have a fundamental deficit in their capacity to understand, represent and manipulate numbers, something he referred to as “numerosity”, and others referred to as “number sense”. Research indicates that very young infants, and even animals, have an innate capacity for detecting and comparing small quantities, and researchers hypothesize that circuitry for the basic processing of numerical information is coded in our DNA (Brannon, 2005). Butterworth (2005) reasoned that this numerical capacity serves as a “starter kit” for the understanding of numbers and mathematics. When this starter kit is defective, the child’s ability to understand and compare numbers is compromised, and the child fails to develop normally in areas pertaining to mathematics.

Dyscalculic children seem to lack this intuitive understanding of number. Even simple tasks such as counting or comparing numerical quantities seem to be difficult for them. Most people can automatically recognize small quantities up to four[14], an ability known as subsitizing. Children with a typical mathematic development learn quite early how to subsitize small sets of three or four. However, children with dyscalculia require more time than their peers to identify small quantities, and some research has shown that dyscalculic children seem to count even small quantities like “3” rather than subsitize (Butterworth, 2005).

The ANS is one model that explains a child’s numerical development. According to this model, the child quickly approximates the quantity, or magnitude, of items without counting, and uses this information to understand, compare and manipulate numerical magnitudes (Morsanyi & Szűcs, 2015). In experiments designed to investigate a person’s ANS, test subjects are often asked to compare non-symbolic representations of numerical magnitude (for example, dots or pictures of small items) and, without counting, to report which quantity is larger or smaller. The ANS model works well when subjects are asked to compare small magnitudes, as reasonably accurate responses can be given quickly. However, with increasing magnitudes (for example, comparing 8 apples to 9 apples), subjects’ approximations become less precise and the subjects’ responses become increasingly inaccurate. The same happens when two quantities are close in magnitude: it becomes increasingly difficult to approximate accurately the larger magnitude of two sets (for example, which is larger: ●●●●●●●● or ●●●●●●●●●).

However, some researchers discount the ANS model. Geary (2015) questioned whether the ANS assists in developing the early foundations for core mathematical skills like learning number words, their cardinality and relative magnitudes, and whether the ANS becomes irrelevant once children have progressed past these foundational skills. Butterworth (2010, p.535) was more critical, and challenged the validity of the ANS model altogether, pointing out that “to be foundational, representations of numbers must be capable of being entered into arithmetic operations.” Butterworth maintained that the ANS is based on non-concrete magnitudes that cannot be used to solve specific arithmetic problems or to reason mathematically. In other words, children cannot use the ANS to learn to count correctly, with one-to-one correspondence, and cannot learn to add and subtract properly using approximate sets.

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[14] Although Kucian and von Aster (2015) wrote that a person’s subsitizing range can be larger if the quantities are presented canonically (in an easily-recognized pattern – such as the patterns found on dominos).

Instead, Butterworth (2010) proposed the “Numerosity Coding Hypothesis,” and asserted that the mental representation of numerosities is a “discrete set” of single units that are ordered in a sequence. The number “5” has a number-concept, or numerosity: “5” is composed of a set of five ordered units. There is a clear, discrete step from one unit (or number) to the next, and this makes it possible to accurately compare magnitudes and manipulate these numerosities to solve mathematical problems. Understanding the relationships between different numerosities and the units that compose these numerosities is important, as this knowledge allows for a solid foundation in a child’s conceptual understanding of number and further mathematical development.

Furthermore, Butterworth (2005) contended that children with dyscalculia have a deficit in this numerosity coding system which leads to a difficulty in enumerating sets. Dyscalculic children’s impaired numerosity representations also affect arithmetic operations like addition. When a child lacks the understanding of numerosities like “5”, it is difficult for that child to conceive of the number itself, or as part of a set. Lacking this basic understanding of the number concept makes it very difficult for the child to understand how to even begin to transform (add, subtract, etc.) numerosities.

Other researchers, however, have written that the dyscalculia’s core deficit is founded in other numerical skills. Rousselle and Noël (2007) disagreed that the core deficit in dyscalculia lies in comparing magnitudes. In Rousselle and Noël (2007), the authors showed that the skills of children with “Mathematical Learning Disabilities” (MLD) in comparing non-symbolic magnitudes was intact, and *similar* to that of their peers. Instead, their research demonstrated that children with MLD were less accurate, and required more time, to discriminate between different *Arabic* numerical symbols compared to their peers. Rousselle and Noël (2007) argued, therefore, that the deficit in mathematical learning disorders is not rooted in *non*-symbolic magnitude comparisons, but in the relationships between the number symbols and their meanings. They termed their theory the “Access Deficit Hypothesis” (ADH), and proposed that it was not the children’s magnitude representations that were impaired, but rather that they had deficits in encoding numerical symbols. Another way of saying this is that children with dyscalculia have more difficulty than their peers in understanding and accessing the meanings and relationships between magnitudes and the number symbols that represent them.

Dyscalculia: behavioral difficulties in solving arithmetic problems

While it is difficult to pin down exactly which cognitive mechanisms lie behind a child’s numerical difficulties, behaviors are more directly measurable. One behavioral characteristic of dyscalculia that has been identified by many researchers involves children’s arithmetic problem-solving strategies. Geary (2010) and Bugden and Ansari (2015) reported that children with dyscalculia have difficulties retrieving number facts from memory, and that they often rely on primitive and inefficient problem-solving strategies to solve arithmetic problems. Snorre Ostad, unlike the previous researchers that study cognitive psychological aspects of dyscalculia, has focused more on behavioral characteristics and pragmatic intervention methods to remediate dyscalculia. In particular, Ostad has studied the problem-solving strategies utilized by children with dyscalculia (Ostad, 2010, 2013).

Typically, children who are learning mathematics initially use simpler, and more concrete strategies to solve arithmetic problems. Through quality educational experiences and practice, they gradually progress to using more efficient and abstract strategies. In Ostad (2013, p. 27), the author arranged different arithmetic problem-solving strategies hierarchically, classifying them as “back-up strategies” or “retrieval strategies.” Geary (2013) has also described “retrieval strategies.”

Back-up strategies use counting methods to solve arithmetic problems. They are called back-up strategies, because children can employ them when they do not know how to calculate an arithmetic problem. When using back-up strategies, children may count verbally or non-verbally, or they may count using their fingers, manipulatives, or by drawing tally marks. Two examples of back-up strategies are “count all” and “count forward” (Ostad, 2010, p.77). “Count all” is, according to Ostad, the most primitive counting strategy and involves counting both quantities separately, and then counting everything together. For example, if “Jane” is going to add “5 + 4”, she will first count five blocks, then count four more blocks, and lastly count all nine blocks to get the answer. This method works, but a child who continues to rely on this time- and energy-consuming strategy will likely begin to run into problems when she is learning to add larger numbers (it is much more difficult to count 14 fingers and then add 23 more without asking several friends for help). This is why it is imperative that children learn more effective ways of solving arithmetic problems.

“Count forward”, on the other hand, is a slightly more advanced counting method. A child who uses this strategy understands that she does not need to count the first five blocks, but can begin to count with the second number. “Count forward” can be illustrated using the same arithmetic problem. Jane would begin with the number “5”, understanding that she will add on to this quantity. Then, Jane will hold up four fingers (or blocks) and count forward using those fingers (“5…. 6, 7, 8, 9”) to find the answer. This is still a counting strategy, but takes less time and energy than the more primitive “count all”.

The other type of problem-solving strategies are retrieval strategies, which are more advanced strategies that do not typically involve counting. Instead, a child that uses retrieval strategies has automated parts of or all of the problem-solving process and no longer needs to count to find the answer. Two examples of retrieval strategies are “direct retrieval” and “decomposition” (Geary, 2003, p. 202). A child who utilizes the strategy “direct retrieval” has completely automated the number fact and can retrieve the answer directly from her memory. “Decomposition” involves retrieving a partial sum from memory (direct retrieval), and then reconstructing, or transforming, the sum to derive the answer. For example, if Jane is going to add “5 + 4”, she first might recall the automated number fact “4 + 4 = 8”. Then, reasoning that five is one more than four, she can just add one to eight to derive the answer. Jane might describe the process this way: “I know that 4 plus 4 is 8, and 5 is one more than 4, so 4 plus 4 (8) plus 1 equals 9.” Another example of a retrieval strategy that involves derivation entails using the opposite operation to solve an arithmetic problem. For example, if Jane needs to subtract five from nine, she may draw on her knowledge of number facts and recall that 5 + 4 = 9, and understanding that addition is the opposite of subtraction, can reasons that 9 – 5 = 4.

Generally, most typically-developing children gradually use more advanced back-up and retrieval strategies as their mathematical skills develop. However, Ostad (2010) pointed out that most children continue to use a mix of strategies throughout their elementary school years. In his study, Ostad (2010, p. 82) found that first-grade children used back-up strategies to solve 94% of simple arithmetic problems. What’s surprising, however, was that when investigating seventh-grade children’s problem-solving strategies, Ostad found that 60% of simple arithmetic problems were still being solved using back-up strategies.

On the other hand, a child with dyscalculia shows a qualitatively different mathematical development when it comes to arithmetic problem-solving strategies. Ostad (2013, p. 22) differentiated children with dyscalculia from children who have more general mathematic difficulties. He argued that children with general mathematical difficulties tend to have a “delayed” mathematical development and often eventually “catch up” with their peers. Contrastingly, children with the specific mathematical disability, dyscalculia, develop in an atypical manner: they generally do not continue to develop their repertoire of strategies, but seem to plateau at the mathematical developmental level of a first or second-grader. Ostad described four behavioral characteristics observed in children with dyscalculia. First, children with dyscalculia choose, almost exclusively, to utilize back-up strategies when solving arithmetic problems. Second, dyscalculic children tend to use the most primitive counting strategies. Third, dyscalculic children have a very small repertoire of strategies from which to choose (usually only one or two strategies), and fourth, there is little change in their strategy development from year to year. Children with dyscalculia, it seems, increasingly struggle with arithmetic because, while their peers have developed more sophisticated and effective strategies for solving arithmetic problems, dyscalculic children continue to use the same effortful, resource-demanding, primitive problem-solving strategies year after year. Solving the problem “61 + 39” by utilizing counting-based back-up strategies is much more difficult than deriving the answer by recalling that “60 + 40 = 100”, and understanding the relationship between these two equations, can simply reason that the answer to “61 + 39” must also be “100”.

So far, I have described some of the theories educational and cognitive researchers have utilized in an attempt to define and explain the many difficulties that children with dyscalculia experience. However, there are other perspectives and research methods that scientists use to investigate dyscalculia – one new area of research that has become involved in the study of children with dyscalculia lies in the field of cognitive neuroscience.

Cognitive Neuroscience and research techniques

Technological advances over the last few decades have led to the genesis of new branches of neuroscience, as well as the development of an extensive knowledge base of brain anatomy. One of these research areas is cognitive neuroscience, the branch of neuroscience that is devoted to understanding complex brain functions like perception, language, memory, emotion, and mathematical or musical abilities. Cognitive neuroscientists use brain-scanning technologies to investigate neural structures and how brain functions are related to cognitive processes and behavior. Two major goals of cognitive neuroscience are identifying different brain regions and networks, and understanding the role of each of these regions and its relationship with other brain areas (Cocchini, 2012; Purves, Mooney, & Platt, 2012; Sternberg & Mio, 2006).

Previously, brain research was usually undertaken using two methods. The first method involved post mortem dissections in which healthy brain structures were compared with diseased, lesioned or damaged brains in an attempt to find connections between the damaged area of the brain and the deceased patient's deficits or disorders existing prior to death. This is called the lesion method, and to a limited extent, is still in use today. The other research method used the brains of live animals, and involved purposely damaging or removing a specific region of the animal's brain. Scientists would then observe and document the resulting loss of function (Purves et al., 2012).

In the 1920s, the first imaging technology, called Pneumoencephalography, came into use. However, this method involved replacing brain fluid with air so that x-ray pictures could be taken, which was a painful and potentially dangerous technique. For these reasons and because it resulted in poor quality pictures, it was not considered an effective method of studying the human brain (Johnsrude & Hauk, 2012; White, Bell, & Mellick, 1973). Then, in the 1970s the use of computers made non-invasive brain-scanning techniques such as Computed Tomography (CT), Positron Emission Tomography (PET) and Magnetic Resonance Imaging (MRI) possible. These techniques allowed researchers to safely and painlessly observe neural activity and structures in living humans, although picture quality was still an issue. However, in 1992, the advent of the functional Magnetic Resonance Imaging (fMRI) machine improved image quality, and neuroscientists finally had a tool with which they could take high-resolution pictures of the human brain in action. This technological development led to an explosion of new research areas, and today cognitive neuroscientists are able to use this technology to create images of human brains while they are engaged in activities that involve information processing, like reading or solving arithmetic problems.

Brain imaging methods

The articles discussed later in this thesis utilized three scanning techniques: Magnetic Resonance Imaging (MRI), Diffusion Tensor Imaging (DTI) and Optimized Voxel-Based Morphometry (OVBM). These three techniques will be explained briefly.

MRI uses magnetic fields and radio waves to record images of anatomical *structures* (*s*MRI), or to record the organization and *functional* (*f*MRI) inner-workings of neural tissue (Johnsrude & Hauk, 2012). These images are not photographs of the brain, but rather record brain activity by measuring the flow of blood to specific neural regions. Neurons, or brain cells, are like all other cells in that they require oxygen to function, and the more neurons are activated, the more oxygen is needed. When oxygen is removed from blood cells, there is a slight change in the magnetic field: this change in magnetic field is recorded by the fMRI machine. To acquire a functional magnetic resonance image, the test subject engages in a cognitive task (e.g., adding two numbers), while the fMRI machine records changes in the magnetic fields as oxygenated blood travels past brain cells and is converted to deoxygenated blood. Data and images recorded by the fMRI machine are statistically analyzed and used to create maps of “brain activation patterns”. However, Johnsrude & Hauk (2012) emphasize that these brain activation patterns are not direct measurements of brain activity, but rather indirect measurements of oxygen consumption that cognitive neuroscientists use to *infer* which brain regions are activated during specific tasks.

MRI machines can also be used to create structural images (sMRI) of the brain while the test subject rests or passively views something. Instead of registering which *areas* are being activated, sMRI machines record the *frequency* of energy being emitted from changes in the magnetic field, and use this data to identify how dense brain regions are. This information is used to create structural maps of brain matter (Johnsrude & Hauk, 2012; Purves et al., 2012).

Two other MRI methods include DTI and OVBM. In order to explain how DTI works, I will first briefly explain basic neural anatomy, as illustrated in figure 1. Neurons are made up of two main parts: the soma, or cell body, and the axon, which transmits nerve signals. The part of the cell containing the soma is referred to as “Gray matter”, and the part containing the axon is referred to as “white matter”. Neurons in brain regions used for cognitive processing are positioned with their soma located towards the outside edge of the brain, while their axons extend towards the inner part of the brain (Purves et al., 2012). These axons are grouped in tracts, or “fibres”, and may extend long distances, connecting different parts of the brain, brain stem, and the spinal cord.

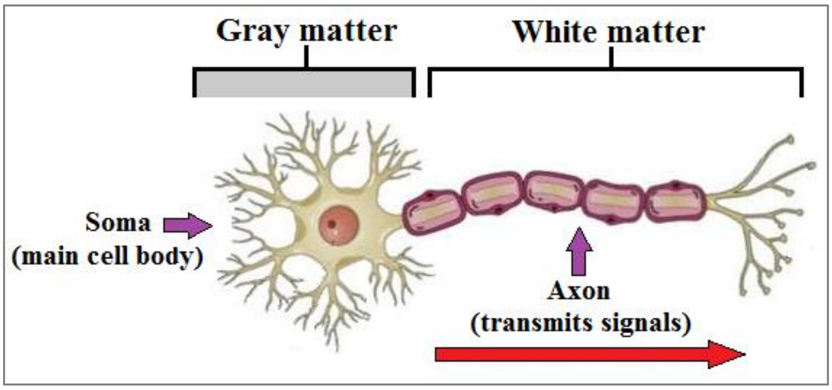

Figure 1. Typical (Multipolar) Neuron[15]

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[15] Figure 1. Neuron picture was acquired from http://buism.com/neurons.htm, but I edited the illustration and added the labels.

DTI is a new imaging technique that records the direction water molecules travel in the axons of neurons. By investigating how water molecules move through these brain fibres, neuroscientists “map” the connectivity of neural networks (Alexander, Lee, Lazar, & Field, 2007). OVBM is not a scanning method, but a statistical method for processing MRI data to compare structural differences in brain anatomy between different groups of test subjects. This information is used to identify trends in differing volumes of brain matter among particular experimental groups (Whitwell, 2009).

Brain activation patterns: localization, network and connectivity perspectives

Müller (2008) explained the development of neuroscience’s two main perspectives, namely the localization and network perspectives. The localization perspective has existed (in various forms) since around 130 AD. It involves identifying specific brain regions and attempting to determine what these brain regions are responsible for (Schmahmann, 2009). A good example of the localization perspective involves Broca’s area. In the 1860s, Pierre Paul Broca discovered that a patient who had suddenly developed speech difficulties had a lesion in the left frontal area of his brain – this led Broca to hypothesize that this brain location was responsible for processing speech, something that he confirmed in numerous other patients (Schmahmann, 2009).

However, other scientists oppose the localization perspective, arguing instead for the network perspective. These scientists contend that the brain is not segmented into isolated units, with each unit being responsible for a specific job. Instead, they argue that different areas of the brain function together in distributed networks. This network perspective has existed for centuries – however, Müller (2008) explained that localization has long been the dominant perspective, mainly because of the technology and research approaches that were available. The lesion method, for example, has historically been the most accessible method for brain research – and Müller explained that localizing models lend themselves to generating clear and falsifiable hypotheses, whereas incorporating lesion data into network models is more complicated and harder to verify. However, since the invention of scanning technologies like fMRI and DTI, cognitive neuroscientists are now able to study the innerworkings of living brains. This allows scientists to investigate both specific brain regions and the networks in which they function.

In addition, cognitive neuroscientists have recently begun to investigate the connectivity of different brain regions that make up neural networks, something that was not possible before.

This study of neural connectivity is a new perspective in neuroscience, but Schmahmann (2009) maintained that this does not mean that the other perspectives should be discounted. Instead, Schmahmann argued that brain loci, networks, and connectivity are all part of an integrated neural system and that none of these perspectives should be overlooked, because all of these perspectives have important aspects that should continue to be investigated.

Summary

In this theoretical chapter, relevant aspects of the study of dyscalculia and neuroscience have been presented. In the first part, dyscalculia was defined as a specific mathematical disability involving distinct numerical deficits. Cognitive perspectives explaining these numerical deficits were discussed, including the Approximate Number System and theories surrounding a deficit in numerical magnitude, the Numerosity Core Hypothesis, and the Access Deficit Hypothesis. In addition, the typical and atypical mathematical development of children was presented, including explanations of children's arithmetic problem-solving strategies and how they are relevant to dyscalculia. In the second part of this theoretical chapter, I explained the development of cognitive neuroscience and neuroscientific brain-scanning methods like fMRI, DTI and OVBM. In addition, three perspectives within cognitive neuroscience were discussed, including the localization perspective, the network perspective and the recent perspective involving connectivity of the brain.

In the next chapters, I will present the results of my literature searches. Subsequently, the results will be analyzed in light of the educational and cognitive neuroscientific perspectives and theories that were presented in this theoretical chapter.

4 Results of literature searches

Literature searches using the four search engines, *Web of Science, PubMed, ERIC* and *PsycNET* were conducted between October 14, 2015 and December 17, 2015. These searches identified two hundred and eighty-seven articles that were related to my search keywords. On February 9, 2016, one follow-up search was conducted using all four search engines to identify research articles that might have been published since December. Five additional articles were identified, one of which satisfied inclusion and exclusion criteria. These five articles were included in the selection process.

Table 3 summarizes the results of my literature searches using the four search engines. A total of two hundred and ninety-two articles were identified, including seventy-nine duplicate articles that were identified by multiple search engines. These seventy-nine duplicates were removed, and the remaining two hundred and thirteen articles were sorted per the inclusion, exclusion and quality criteria.

Table 3. Summary of results using the four search engines

Search engine	Number of articles identified	Non-duplicate articles of prior searches
Web of Science	112	112
PsycNET	60	24
PubMed	114	77
ERIC	6	0
Total articles	292 articles	213 non-duplicate articles

The article selection process is summarized in figure 2. The first step of the selection process involved scanning article titles and abstracts to identify all articles that might fit the inclusion and exclusion criteria. Eighty-three articles were identified as being potentially relevant, while one hundred and thirty articles were discarded as they were not relevant to my research topic. Examples of articles that were excluded as part of step 1 were neurological studies of patients with Alzheimer’s disease, Turner’s syndrome, or brain injuries that referenced mathematical abilities.

In step 2, I scanned the eighty-three article texts and filtered the articles according to my inclusion and exclusion criteria. Forty-eight articles were discarded (for example, articles that had the wrong topic or studies using adults instead of children). This scanning process resulted in thirty-five relevant articles that seemed to fit the inclusion and quality criteria.

Step 3 of the selection process involved reading and tabulating all thirty-five articles. Information about the articles' quality, focus, research questions, experimental procedures, analysis and discussions were tabulated using MS Excel. As a result of this process, sixteen articles were identified as satisfying all of my research criteria and were included in my corpus. The seventeenth article, Kucian, et al. (2006), satisfied all the inclusion criteria, but came from a journal with a Q3 rating – possibly because 2006 was the first year the journal had ever been published. However, I decided to include this article in my corpus because it was a landmark article and it was an article that most of the other articles referred to.

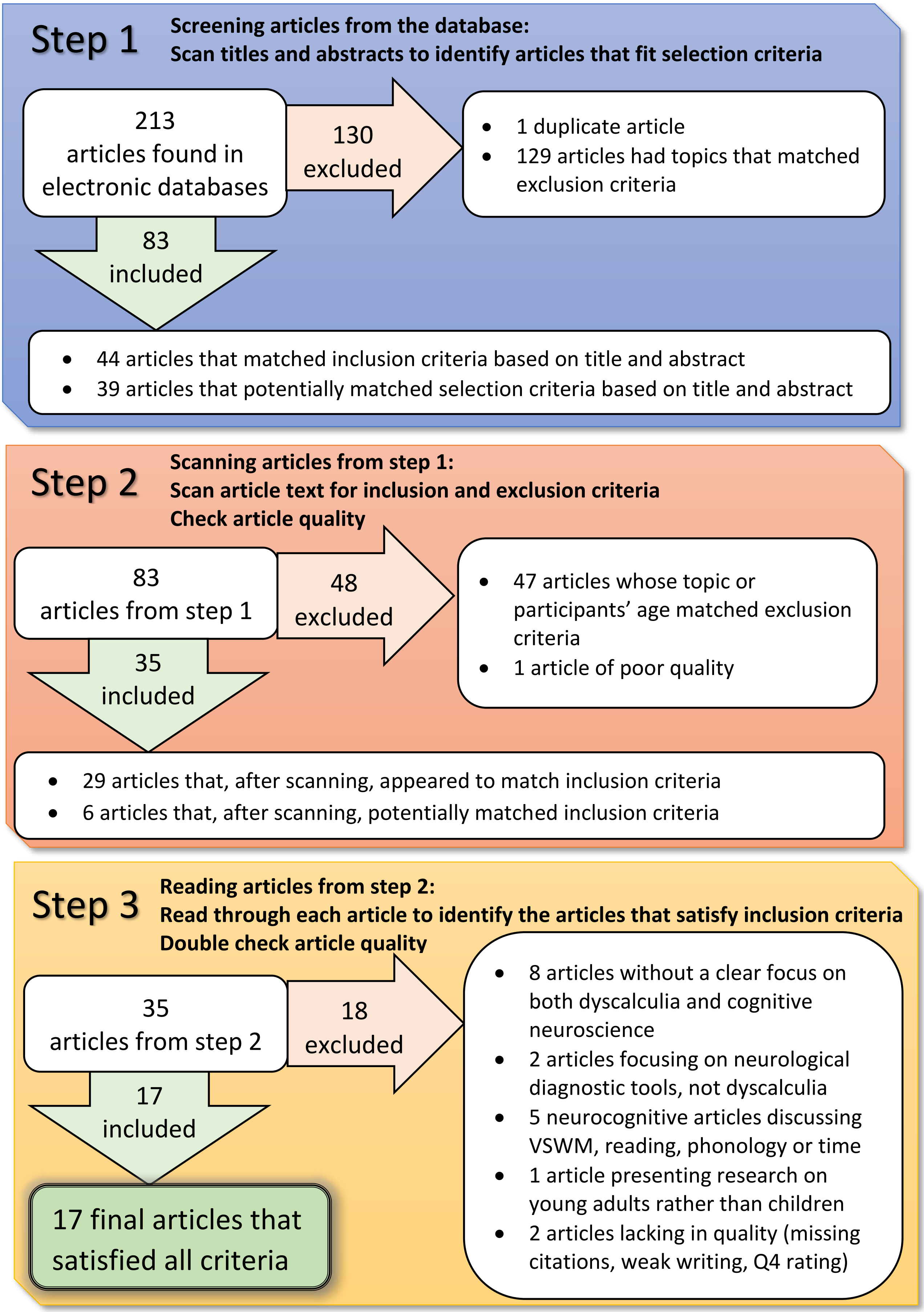

Figure 2. Literature search and identification summary

In the next step of my systematic literature review, I analyzed the articles and found that multiple patterns emerged from the data. First, the articles fell into one of two categories: literature reviews of neurocognitive research on dyscalculia, or scientific articles reporting the results of neurocognitive research on dyscalculia. Table 4 summarizes the *four review* articles that discussed neurocognitive research on children with dyscalculia.

Table 4. Review articles about neurocognitive research and dyscalculia

Title, author, publication information	Summary
Kucian, K., & von Aster, M. (2015). Developmental dyscalculia. *European Journal of Pediatrics*	Discusses the mathematical and neurological development of children with dyscalculia, and factors related to diagnosis and intervention.
Butterworth, B., Varma, S., & Laurillard, D. (2011). Dyscalculia: From Brain to Education. *Science*	Presents a model of dyscalculia from a behavioral and cognitive neurological standpoint, and discusses implications for diagnosis and intervention.
Kaufmann, L., Wood, G., Rubinsten, O., & Henik, A. (2011). Meta-Analyses of Developmental fMRI Studies Investigating Typical and Atypical Trajectories of Number Processing and Calculation. *Developmental Neuropsychology*	Systematically reviews 19 fMRI studies about factors involved in the typical and atypical mathematical development of children.
Rubinsten, O., & Henik, A. (2009). Developmental Dyscalculia: heterogeneity might not mean different mechanisms. *Trends in Cognitive Sciences*	Presents three neurocognitive models for the understanding of dyscalculia and mathematical learning disorders.

Table 5 summarizes the *thirteen neurocognitive research articles* on dyscalculia. Of these thirteen articles, eleven presented research utilizing fMRI to compare the brain activation patterns of children with dyscalculia to children with a typical mathematical development as the children were actively engaged in various numerical tasks. Two articles presented research using sMRI techniques to compare children’s brain volumes as well as gray and white brain matter structure in children with and without dyscalculia. These techniques included DTI and OVBM.

Table 5. Dyscalculia research using the brain-scanning methods fMRI, DTI and OVBM

Title, author, publication information	Summary
Rosenberg-Lee, M., Ashkenazi, S., Chen, T. W., Young, C. B., Geary, D. C., & Menon, V. (2015). Brain hyper-connectivity and operation-specific deficits during arithmetic problem solving in children with developmental dyscalculia. *Developmental Science*	FMRI experiment investigating the brain activation patterns of children, both with typical mathematical development and with dyscalculia, while they engage in addition and subtraction tasks.
Iuculano, T., Rosenberg-Lee, M., Richardson, J., Tenison, C., Fuchs, L., Supekar, K., & Menon, V. (2015). Cognitive tutoring induces widespread neuroplasticity and remediates brain function in children with mathematical learning disabilities. *Nature Communications*	FMRI experiment comparing the brain activation patterns of children with and without dyscalculia before and after participating in an eight-week, instructor-led tutoring program.
Kucian, K., Ashkenazi, S. S., Hanggi, J., Rotzer, S., Jancke, L., Martin, E., & von Aster, M. (2014). Developmental dyscalculia: a dysconnection syndrome? *Brain Structure & Function*	DTI experiment comparing white matter microstructure (connective fibres) in children with and without dyscalculia.
Ashkenazi, S., Rosenberg-Lee, M., Tenison, C., & Menon, V. (2012). Weak task-related modulation and stimulus representations during arithmetic problem solving in children with developmental dyscalculia. *Developmental Cognitive Neuroscience*	FMRI experiment comparing brain activation patterns of children with dyscalculia and with typical mathematical development while engaging in addition tasks.
Kucian, K., Grond, U., Rotzer, S., Henzi, B., Schonmann, C., Plangger, F., . . . von Aster, M. (2011). Mental number line training in children with developmental dyscalculia. *Neuroimage*	FMRI experiment comparing the brain activation patterns of children with and without dyscalculia before and after a 5-week intervention using a computer-based tutoring program.
Kucian, K., Loenneker, T., Martin, E., & von Aster, M. (2011). Non-Symbolic Numerical Distance Effect in Children With and Without Developmental Dyscalculia: A Parametric fMRI Study. *Developmental Neuropsychology*	FMRI experiment investigating the neural activation patterns of children with and without dyscalculia while they engage in a non-symbolic numerical magnitude comparison task.
Mussolin, C., De Volder, A., Grandin, C., Schlogel, X., Nassogne, M. C., & Noel, M. P. (2010). Neural Correlates of Symbolic Number Comparison in Developmental Dyscalculia. *Journal of Cognitive*	FMRI experiment comparing the brain activation patterns of children with dyscalculia and with typical mathematical development while engaging in a numerical magnitude comparison task.

Kaufmann, L., Vogel, S. E., Starke, M., Kremser, C., & Schocke, M. (2009). Numerical and non-numerical ordinality processing in children with and without developmental dyscalculia: Evidence from fMRI. *Cognitive Development*	FMRI experiment comparing the brain activations of children with and without dyscalculia while engaging in symbolic and non-symbolic ordinality tasks.
Davis, N., Cannistraci, C. J., Rogers, B. P., Gatenby, J. C., Fuchs, L. S., Anderson, A. W., & Gore, J. C. (2009). Aberrant functional activation in school age children at-risk for mathematical disability: A functional imaging study of simple arithmetic skill. *Neuropsychologia*	FMRI experiment describing the brain activation patterns of children with and without dyscalculia while they engaged in approximate and exact calculation tasks.
Kaufmann, L., Vogel, S. E., Starke, M., Kremser, C., Schocke, M., & Wood, G. (2009). Developmental dyscalculia: compensatory mechanisms in left intraparietal regions in response to nonsymbolic magnitudes. *Behavioral and Brain Functions*	FMRI experiment comparing the neural activation patterns of children with dyscalculia and with typical mathematical development while engaging in a non-symbolic numerical magnitude task.
Rotzer, S., Kucian, K., Martin, E., Aster, M. v., Klaver, P., & Loenneker, T. (2007). Optimized voxel-based morphometry in children with developmental dyscalculia. *Neuroimage*	OVBM experiment comparing gray and white matter volumes in the brains of children with and without dyscalculia.
Price, G. R., Holloway, I., Rasanen, P., Vesterinen, M., & Ansari, D. (2007). Impaired parietal magnitude processing in developmental dyscalculia. *Current Biology*	FMRI experiment investigating the differences in brain activation related to numerical distance effects in children with and without dyscalculia, while they engage in a non-symbolic numerical comparison task.
Kucian, K., Loenneker, T., Dietrich, T., Dosch, M., Martin, E., & von Aster, M. (2006). Impaired neural networks for approximate calculation in dyscalculic children: a functional MRI study. *Behavioral and Brain Functions*	The first FMRI experiment investigating differences in brain activation patterns in children with and without dyscalculia. The children engaged in numerical magnitude comparison, and approximate and exact calculation tasks.

Another pattern that emerged from the data involved the neuroscientific and pedagogical perspectives the authors employed in discussing their results. These perspectives fell into two categories: neurological perspectives regarding how the brain works in regard to dyscalculia and educational perspectives on dyscalculia discussed within the context of neurological research. These patterns will be discussed in part one of the analysis section in order to answer my first research question, “What does recent research on cognitive neuroscience have to say about dyscalculia?”.

Lastly, there were four articles that discussed or reported experimental results involving interventions for the remediation of dyscalculia. These articles will be discussed in part two of the analysis chapter in order to answer my second research question, “What does neurological research on dyscalculia say about the effect of interventions on children’s learning?”.

5 Analysis

This chapter is composed of two parts, each of which will address one of my two research questions. My first research question, "*What does recent research on cognitive neuroscience have to say about dyscalculia?"*, will be explored in part one, in which I will analyze recurring themes from the seventeen cognitive neuroscientific articles. Three themes will be discussed: 1.) perspectives of cognitive neuroscience related to mathematical development and brain activation patterns, 2.) perspectives of cognitive neuroscience as related to the heterogeneity of dyscalculia and 3.) educational perspectives on dyscalculia as related to domain-specific and domain-general processing mechanisms.

In part two, I will address my second research question, "*What does neurological research on dyscalculia say about the effect of interventions on children's learning?".* The four articles presenting research on interventions for the remediation of dyscalculia will be analyzed in light of the theoretical perspectives and the first part of the analysis.

Part one: Cognitive neuroscientific research on dyscalculia

Cognitive neuroscientific perspectives on brain development, activation patterns and dyscalculia

Perspectives within cognitive neuroscience have changed dramatically, especially in regard to the understanding of children's neural development. The first fMRI research study on children with dyscalculia in 2006 by Kucian et al., identified significant differences in how children and adults process mathematical information. This has been confirmed repeatedly by other neurocognitive experiments, which have reported that children's brain activation patterns and connectivity change substantially as they develop as a result of experience, brain maturation and the ongoing development of mathematical knowledge. As a result, researchers like Butterworth et al. (2011), Iuculano et al. (2015), Kaufmann, Vogel, Starke, Kremser, Schocke, et al. (2009) and Rubinsten and Henik (2009) have concluded that neurological models of mathematical processing in adults may not be relevant to the study of children's numerical development. Kucian and von Aster (2015) wrote that "direct comparison of mature and developing brain systems may not be feasible due to considerable differences regarding brain structure and function." These researchers seem to be in agreement that new models are needed that take into account the neurodevelopment of children's numerical processing.

At the same time, previous cognitive neuroscientific research on adults has overwhelmingly indicated that the intraparietal sulcus (IPS) is an important brain region for the processing of numerical information. Recent neurocognitive research on children, including all of the articles in this study, has also indicated that the r.IPS is an important brain region for mathematical processing, although many researchers also point out that the r.IPS is not the *sole* area responsible for mathematical processing. This neuroscientific discussion on the r.IPS is an excellent example of the debate over the localization and network perspectives. References to these neurocognitive perspectives were evident in all of the seventeen articles, as summarized in table 6.

Table 6. Perspectives within cognitive neurology. Articles highlighted in blue referred mainly to the localization perspective, articles highlighted in yellow referred primarily to the network perspective, and articles highlighted in pink emphasized brain connectivity.

Article	**Perspective the article referred to**
Rosenberg-Lee et al., 2015	Mainly connectivity, but also discussed network and localization
Iuculano et al. (2015)	Network
Kucian & von Aster, 2015	Network, mentioned connectivity.
Kucian et al., 2014	Connectivity, also discusses the network perspective
Ashkenazi, Rosenberg-Lee, Tenison, & Menon, 2012	Mainly localization, but also mentioned connectivity and network perspectives
Kucian, Grond, et al., 2011	Mainly network, but also referred to localization and connectivity perspectives
Butterworth et al., 2011	Mainly network, but also discusses connectivity
Kucian, Loenneker, Martin, & von Aster, 2011	Network
Kaufmann, Wood, Rubinsten, & Henik, 2011	Network
Mussolin et al., 2010	Localization
Kaufmann, Vogel, Starke, Kremser, & Schocke, 2009	Localization
Davis et al., 2009	Network, but mentioned localization
Kaufmann, Vogel, Starke, Kremser, Schocke, et al., 2009	Localization
Rubinsten & Henik, 2009	Network
Rotzer et al., 2007	Both network and localization perspectives
Price, Holloway, Rasanen, Vesterinen, & Ansari, 2007	Localization
Kucian et al., 2006	Network

Supporting Müller (2008)'s claims that the localization model has been the dominating perspective due to technological limitations and research methods, most of the earlier research articles in this study reflect Müller's statement, as can been seen from table 6. Of the seventeen articles in this thesis, nine articles have a particular focus on specific brain regions like the IPS, and five of the six articles published prior to 2011 were written from the localization perspective. Price et al. (2007) wrote that their results provided "direct evidence for a specific impairment of parietal magnitude systems in DD during non-symbolic numerosity processing." Price's team identified areas within the parietal and frontal lobes (r.IPS, l.FG and l.MPFG)[16] presumed to be responsible for numerical magnitude processing and visual segmentation, and hypothesized that these neural regions were deficient in children with dyscalculia. Kaufmann, Vogel, Starke, Kremser, Schocke, et al. (2009) described specific areas in the left intraparietal regions which the authors suggested were responsible for specific compensatory mechanisms during non-symbolic magnitude comparison tasks, and Mussolin et al. (2010) reported areas in the right and left IPS, r.MFG and l.CG that were deactivated in children with dyscalculia. Mussolin et al. (2010) also quoted fourteen studies confirming the importance of the IPS for tasks involving numerical processing, approximation, magnitude comparison, numerosity, change detection, subsitizing, counting, and numerical distance effects. They proposed a direct causal relationship between brain activation patterns in the left and right IPS and the dyscalculic profile. In addition, Rotzer et al. (2007), Kaufmann, Vogel, Starke, Kremser, and Schocke (2009) and Kaufmann, Vogel, Starke, Kremser, Schocke, et al. (2009) pinpointed areas in the r.IPS that were related to numerical processing. Ashkenazi, Rosenberg-Lee, Tenison, and Menon (2012) detailed areas in the parietal lobe, including the IPS, SPL and SMG, and argued that these areas were specifically involved in cognitive processes involving numerical problem solving. Ashkenazi and colleagues also and reported relationships between the IPS and numerical quantity representation and semantic number processing, and areas in the SPL and SMG, which were reported as being involved in visuo-spatial working memory and attention.

Nevertheless, the dominating perspective identified in the seventeen articles was the network perspective, which was referred to in thirteen articles. Cognitive neuroscientists have begun referring to this perspective more frequently, arguing that specific areas of the brain do not

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[16] Abbreviations of brain areas are listed in chapter 8.

work in isolation, but rather function in connected networks to process mathematical information. Iuculano et al. (2015, p.5) explained that

> although MLD was initially conceptualized as a disorder of a single brain region characterized by a local deficit in the intraparietal sulcus, more recently, prominent neurocognitive models of MLD have posited that the disorder stems from more extensive functional aberrations in a distributed network of brain areas encompassing not only posterior parietal, but also prefrontal, as well as ventral temporal-occipital cortices that are known to serve multiple cognitive functions necessary for successful numerical problem solving.

Rubinsten and Henik (2009) objected to the idea that one single abnormality in the IPS is the sole cause of dyscalculia. Instead, they pointed out that multiple aspects of numerical processing involve not only the IPS, but also networks involving the l.IFL, the l.AG and left l.FG. Kucian et al. (2006) noted atypical brain activation patterns in practically the entire neuronal network for tasks involving approximate calculation. Davis et al. (2009), Kaufmann, Wood, Rubinsten, and Henik (2011), Kucian, Grond, et al. (2011) and Kucian, Loenneker, Martin, and von Aster (2011) described "several distinct but functionally interrelated networks" (Davis et al., 2009) that are involved in numerical processing. This includes brain systems supporting domain-general processing, and networks supporting domain-specific (mathematical) processing. Kucian and von Aster (2015) confirmed that the IPS is a core locus of numerical processing and quoted studies (on both humans and monkeys) that identified brain activation in this network - although Kucian and von Aster also wrote that other neuronal networks are involved, including brain regions associated with domain-general capacities, like the PFC.

> Numerical processing and calculation are a demanding cognitive ability which is processed by a complex neuronal network. In addition to the key areas for numerical cognition located in the parietal lobes, prefrontal cortices, regions associated with the dorsal and ventral visual pathways, as well as sub-cortical areas and the cerebellum play a significant role in numerical tasks. (Kucian & von Aster, 2015, p.7)

Recently, however, a third perspective has emerged in cognitive neuroscientific research on dyscalculia, namely a focus on brain connectivity, or how information travels through different neural networks. Table 6 identifies five articles, all published after 2010, that discuss the connections between different neural networks. Two articles, Rosenberg-Lee et al. (2015)'s fMRI study, and Kucian et al. (2014)'s DTI study focused on the connections between different brain areas, and one article (Butterworth et al., 2011) discussed both connectivity as well as shifting networks. In their experiment, Rosenberg-Lee et al. (2015)

identified, in children with dyscalculia, a “hyperconnectivity” between the IPS and core areas of the DMN (a network of brain areas that are typically deactivated during tasks that are cognitively demanding), and between the IPS, LFPC and PFC (which assist with domain-general processing mechanisms like attention, working memory and planning.) Kucian et al. (2014) used DTI to investigate the microstructures of neural connecting fibres, and reported a deficient fibre projection between the parietal, temporal and frontal brain regions in children with dyscalculia. Kucian et al. (2014) wrote that: “fibres connecting the key region for numerical representation with other areas necessary for numerical processing and calculation are impaired or developmentally delayed in children with DD.” Taken together, the findings of these authors may indicate that neural connectivity might be part of the reason why children with dyscalculia have difficulty in processing and learning mathematical information. However, the causality of these findings is uncertain, because impaired connectivity could also be a temporary side effect of children’s learning patterns and their developmental levels, since children’s brains continuously establish, strengthen and abandon pathways for processing information. Additional research is needed before causality can be determined.

Another aspect of the data involves brain activation patterns. All of the articles reported results that the children with dyscalculia had shown increased or decreased brain activation or brain matter. Table 7 presents the brain activation pattern results as reported by each of the seventeen articles.

It is interesting to note that the experimental results reported by these articles show very conflicting results. For example, *six* articles reported that, compared with control children, children with dyscalculia had *decreased* brain activation (Ashkenazi et al., 2012; Butterworth et al., 2011; Kucian et al., 2006; Price et al., 2007), or *decreased* brain matter volume/density (Kucian et al., 2014; Rotzer et al., 2007) in key mathematical processing areas. Contrastingly, *six* articles reported *increased* brain activation patterns for children with dyscalculia (Davis et al., 2009; Iuculano et al., 2015; Kaufmann, Vogel, Starke, Kremser, & Schocke, 2009; Kaufmann, Vogel, Starke, Kremser, Schocke, et al., 2009; Kucian, Loenneker, et al., 2011; Rosenberg-Lee et al., 2015). Moreover, *five* articles reported mixed results, indicating *both increased and decreased* brain activation patterns in various regions of the neural network for children with dyscalculia compared with their peers. These widely varying experimental results, however, is unsurprising considering how new the field is, and considering that researchers lack clear definitions and guidelines for diagnosing dyscalculia. What is clear, however, is that neurocognitive research on children identifies clear differences between the brain activation patterns of children with dyscalculia and children with a normal mathematical development.

Table 7. Articles' reported experimental results. Articles highlighted in yellow recorded increased brain activation in children with dyscalculia, articles in blue recorded both increased and decreased brain activation, and articles in red reported decreased brain activation or decreased amounts of brain matter in children with dyscalculia.

Article	**Activation results in research: ↑ = increased, ↓ = decreased or ↓↑ = mixed activations in the brains of children with dyscalculia**
Rosenberg-Lee et al., 2015	↑ increased brain activation
Iuculano et al. (2015)	↑ increased brain activation
Kucian & von Aster, 2015	↓↑ mixed brain activations
Kucian et al., 2014	↓ decreased white matter volume
Ashkenazi, Rosenberg-Lee, Tenison, & Menon, 2012	↓ decreased brain activation
Kucian, Grond, et al., 2011	↓↑ mixed brain activations
Butterworth et al., 2011	↓ decreased brain activation
Kucian, Loenneker, Martin, & von Aster, 2011	↑ increased brain activation
Kaufmann, Wood, Rubinsten, & Henik, 2011	↓↑ mixed brain activations
Mussolin et al., 2010	↓↑ mixed brain activations
Kaufmann, Vogel, Starke, Kremser, & Schocke, 2009	↑ increased brain activation
Davis et al., 2009	↑ increased brain activation
Kaufmann, Vogel, Starke, Kremser, Schocke, et al., 2009	↑ increased brain activation
Rubinsten & Henik, 2009	↓↑ mixed (referred to many articles)
Rotzer et al., 2007	↓ decreased grey & white matter volume
Price, Holloway, Rasanen, Vesterinen, & Ansari, 2007	↓ decreased brain activation
Kucian et al., 2006	↓ decreased brain activation

Research findings like these are important because they influence our understanding of, and attitudes towards children with dyscalculia. When researchers use words like "deficient" or "dysfunctional" to describe the functioning, brain matter or connectivity of the brains of children with dyscalculia, it is understanding that one might adopt the belief that dyscalculic children’s brains are faulty. Results stating that children with dyscalculia have decreased brain activation or less brain volume can easily be understood by the public as “Children with dyscalculia are less intelligent”, or “There is something wrong with dyscalculic children’s brains”.

Educators who believe that children with dyscalculia have faulty, defective or dysfunctional brains may treat the child differently than his peers. The focus in the educational setting can easily fall on the child’s weaknesses and defects: which will influence how school personnel work with dyscalculic children. They may believe that therapists and doctors must do something to “fix” these children’s brains so that they fit into the educational system and its expectations – or, even worse, school personnel may believe that this is an impossible task: the child is “disabled” and has no hope for improvement. This type of attitude could lead them to believe that the best way to help the child is to adjust the learning materials so that the child always gets simple, routine math problems.

While this negative focus on the child’s defects and dysfunctions may be a valid interpretation of the experimental results of neurocognitive research on dyscalculia, believing that the brains of children with dyscalculia are faulty will not produce a positive learning environment or future outlook for the child. Instead, this negative focus will impact how the teacher interacts with her students. This negative attitude could be communicated implicitly to the child, who is already acutely aware of how difficult mathematics is for him compared with his peers, and that he lacks abilities while his classmates seem to manage with ease. A child with dyscalculia repeatedly experiences that he does not live up to the expectations of his teachers and parents. This child often feels insecure, believing that he is stupid because he “just doesn’t get it.”

Being assigned simple math problems or receiving extra, or simplified instruction may reinforce the child’s negative interpretation of the situation. In addition, an educator without an understanding of dyscalculia may believe that repetition will help, and reteach the same material using the same methods. The child then experiences repeatedly that he can’t master the tasks, which can lead him to feel demotivated, helpless, hopeless and stupid, which may cause him to stop trying to improve. The child’s educators and caregivers may also begin to feel frustrated or helpless and begin to lose hope.

Clear communication must exist between cognitive neuroscientists, educational professionals and the public - communication that does not focus too heavily on dyscalculic children’s weaknesses and “dysfunctional” brains, nor should it communicate dire results with no chance of for improvement. Educational professionals must consciously foster a positive focus in the interaction with the child, his family and school personnel, by focusing on the child's strengths and positive attributes. It is also vital that a clear plan is developed and possible interventions are discussed with everyone involved, including the child.

Another reason the results from these articles are important is because they can lead to increased discussion and information on dyscalculia. Results from cognitive neuroscientific experiments about the neurodevelopment of children with dyscalculia can help to identify specific processing problems children may have – information which can be used to create better definitions of dyscalculia, to refine diagnosis criteria, and to develop better diagnostic tools. Experimental results identifying neurodevelopmental differences between children with dyscalculia and their non-dyscalculic peers also give credence to dyscalculia as a legitimate learning disability. Educators can read these results and say, "dyscalculia is a real disability, just as dyslexia is real, and children with dyscalculia can also be helped". In addition, these results can be used to design more effective interventions for children with dyscalculia.

Cognitive neuroscientific perspectives on dyscalculia as a heterogeneous or homogenous disability

Heterogeneity refers to the diversity of a population, and is part of a debate in the study of dyscalculia. Some cognitive researchers assert that dyscalculics comprise a homogeneous group and that all children with dyscalculia have one specific impairment in numerical processing. Other researchers maintain that children with dyscalculia are a diverse group of individuals who may have difficulties with multiple aspects of mathematics. In this thesis, the majority of the articles addressed heterogeneity. However, even the articles that did not explicitly refer to the heterogeneity of dyscalculia were nonetheless influenced by their unstated perspectives, as those perspectives affected all of the experimental results of these articles, and thus is an extremely salient issue. Table 8 identifies the eleven articles that explicitly addressed their position on the heterogeneity or homogeneity of dyscalculia.

Table 8. Researchers' perspectives on the heterogeneity of dyscalculia. Articles with a homogeneous perspective of dyscalculia are highlighted in gray.

Article	**Perspective**
Iuculano et al. (2015)	Heterogeneous
Kucian & von Aster, 2015	Heterogeneous
Kucian et al., 2014	Heterogeneous
Butterworth et al., 2011	Homogeneous
Kucian, Loenneker, Martin, & von Aster, 2011	Heterogeneous
Mussolin et al., 2010	Heterogeneous
Kaufmann, Vogel, Starke, Kremser, Schocke, et al., 2009	Heterogeneous
Rubinsten & Henik, 2009	Heterogeneous
Rotzer et al., 2007	Heterogeneous
Price, Holloway, Rasanen, Vesterinen, & Ansari, 2007	Homogeneous
Kucian et al., 2006	Heterogeneous

Butterworth et al. (2011) and Price et al. (2007) maintained that dyscalculia is a homogeneous disability involving *specific deficits*. Butterworth et al. (2011) asserted that dyscalculia is a "coherent syndrome" reflecting a core deficit in processing numerosities. Price et al. (2007) referred to pure Developmental Dyscalculia (pDD), stating that children with pDD show deficits in elementary numerical processing due to impairments in numerical representation and the processing of numerical magnitude. Furthermore, although these authors did acknowledge that other factors (e.g. reading ability, or impairments in domain-general processing mechanisms, like attention) influence children's abilities to learn mathematics, Butterworth et al. (2011) and Price et al. (2007) emphasized that dyscalculia is a homogeneous learning disability that is due to a domain-specific impairment rooted in numerical processing difficulties.

Contrastingly, the authors of other nine articles[17] argued that children with dyscalculia are part of a heterogeneous, rather than homogeneous, group, because the cognitive and

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[17] Kucian was involved in writing five of these nine articles, including: (Kucian et al., 2014; Kucian et al., 2006; Kucian, Loenneker, et al., 2011; Kucian & von Aster, 2015; Rotzer et al., 2007), so these articles share cognitive neuroscientific perspectives.

behavioral profiles of these children vary, and because comorbid learning disorders (e.g., dyslexia and ADHD) are common. Iuculano et al. (2015), Kucian and von Aster (2015) and Rubinsten and Henik (2009) explained that neurocognitive research has identified multiple functional and structural abnormalities in a widespread neural network in dyscalculic children, and that multiple brain abnormalities would explain the differing cognitive profiles of children with dyscalculia. This is because abnormal brain activation patterns were identified in neural regions believed to be involved in multiple types of cognitive functions – including both domain-specific (numerical processing) and domain-general processing mechanisms. Furthermore, dysfunctions in these areas could result in numerous impairments in cognitive processing. Kucian and von Aster (2015) also pointed out that numerical processing comprises both numerical and non-numerical competencies (including visual-spatial abilities and working memory), and, since the strengths and weaknesses of individual children with dyscalculia differ, their mathematical competencies will also differ as a result.

Rubinsten and Henik (2009) based their definition on statistics, and argued for both sides: they referred to two types of dyscalculia: pDD and dyscalculia with comorbid conditions (cDD). However, Rubinsten and Henik (2009) asserted that dyscalculia should be considered a *heterogeneous* disability because the children with pDD are in the minority: the majority of children with dyscalculia have cDD, meaning that the learning profiles of children with dyscalculia can vary greatly.

Although there is a general consensus that the expected prevalence rate for dyscalculia is 3-7% of the general population, there is not a consensus regarding all of the cognitive difficulties attributed to dyscalculia. Moreover, not even the authors of these seventeen articles agreed on these statistics, and not all of them chose research populations which matched the expected prevalence rate[18].

Five articles[19] strictly adhered to the expected rates, including in their experimental (dyscalculic) groups children scoring at least 1.5 standard deviations below the norm on their diagnostic tests (approximately 6.7% of the sample population). However, Rosenberg-Lee et

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[18] Many researchers do not align their research populations to match the 3-7% estimate. Three examples of this include: Ashkenazi et al. (2012) who chose the lowest 25% to be in their dyscalculic group and 37% or higher as their control group, Davis et al. (2009) who chose the lowest 25% for their dyscalculia group and top 49% as their control group, and Mussolin et al. (2009) who chose children that showed at least a 2-year delay in their mathematical development.

[19] Kucian et al. (2014), Kucian, Grond, et al. (2011), Kaufmann, Vogel, Starke, Kremser, Schocke, et al. (2009), Kaufmann, Vogel, Starke, Kremser, and Schocke (2009) and Price et al. (2007)

al. (2015) asserted that up to 25% of children have a mathematical learning disability, and so they matched their research populations accordingly. Rosenberg-Lee et al.’s experimental (dyscalculic) group was comprised of children scoring at or below the 25th percentile on an assessment test, while their control group included children scoring between the 75th and the 94th percentiles. If the expected 3-7% prevalence rate is accurate, this means that Rosenberg-Lee and colleagues likely included children in their dyscalculic group that were low-performing in math, but did not necessarily have dyscalculia. In addition, Rosenberg-Lee et al.’s control group were high-performers, with mathematical skills that are well above average.

Another research article that deviated from the 3-7% estimate is Iuculano et al. (2015), who estimated that up to 20% of children had a MLD. In their experiment, they compared children that scored at or below 16% (dyscalculic group) on the assessment test with children that scored at 25% or above (control group). This means that some of the children in Iuculano et al.’s control group might have been placed in the dyscalculic group from Rosenberg-Lee et al. (2015) if they had participated in that study.

Another way perspectives on heterogeneity affect the experimental results of cognitive neuroscientific research involves the diagnostic assessments used. Researchers in different countries use different types of assessment tools to identify students with dyscalculia. Some researchers use the scores from standardized, written achievement tests to determine their experimental groups[20]. Other researchers use dyscalculia screeners, mathematical assessment tests or the numerical sections of intelligence tests. The problem with this is that different diagnostic and standardized tests assess different areas of mathematics and can include tasks assessing multiple learning domains, instead of just testing mathematical ability.

National laws and policies can also affect the comparison of experimental results. For instance, Kucian’s and Rotzer’s research is conducted in Zürich, where the governing body has decided that the assessment results of children with dyscalculia may not be shared, not even anonymously (Rotzer et al., 2007). For this reason, Kucian’s and Rotzer’s research publications state only that the children in their studies were “diagnosed” by educational professionals or psychologists. Unfortunately, this means that Kucian and Rotzer’s

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[20] Researchers’ use of standardized achievement tests as tools for the diagnosis of dyscalculia is particularly common with researchers from the U.S.A. like David Geary, whose research in MLD has been particularly influential. Geary and colleagues generally adhere to a 25% prevalence rate in their research.

experimental results cannot be directly compared to the results of other experiments, since it is not possible to compare their experimental populations.

Yet another variable complicating the comparison of neurocognitive (as well as behavioral) research involves the children's ages. Some researchers used seven-year-olds as test subjects, while others used eleven-year-olds. Two research studies that may have been significantly affected by age differences include Kucian, Loenneker, et al. (2011) and Kucian et al. (2006), whose research studies included both 9 and 12 year-olds. Nine and twelve-year-old children are at different stages of their mathematical development and education, and their brain activation patterns reflect this. Combining the neural activation patterns of both the nine and twelve-year-old experimental groups into one mixed-age control and one mixed-age dyscalculic group, could have compromised their fMRI data[21]. Kucian et al. (2006) wrote that there was much greater variability in the neural activation patterns of individuals in the dyscalculic groups than in the control groups. Greater variability could be explained by the fact that the authors compared heterogeneous groups of dyscalculic children - particularly children at different ages and developmental levels. Furthermore, if some of the children in the experimental group had dyscalculia while others in the same group had a MLD, their brain activation patterns could vary accordingly. The activation patterns of the control group (children with a "typical" mathematical development), on the other hand, could be expected to be more similar in terms of mathematical processing.

This variability in neuroscientists' definitions of dyscalculia, experimental populations and methods significantly affects experimental results and makes comparisons between research studies difficult. This also makes drawing conclusions difficult and hinders the development of knowledge on dyscalculia.

This debate on the heterogeneous or homogeneous nature of dyscalculia is a difficult one to resolve. Butterworth et al. (2011) and Kucian and von Aster (2015) present opposing viewpoints on the use of homogeneous or heterogeneous experimental groups. While Butterworth et al. (2011) asserted that homogeneous groups are vital if scientists are to understand the true nature and cognitive mechanisms of dyscalculia. On the other hand, Kucian and von Aster (2015, p.10) argued that the:

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[21] Mixing these age groups also affected the behavioral results of Kucian et al. (2006). This is discussed in more detail in the next section on educational perspectives, and an example is given in Appendix A.

> Artificial restriction of most research on pure DD is missing the point that DD children with additional comorbidities is the rule and not the exception. Although it is possible to keep your examination cohorts as homogeneous as possible to draw clear conclusions, future research should focus on children who reflect rather reality, namely DD children with comorbid disorders.

Kucian and von Aster (2015) argued further that dividing children with dyscalculia into different subgroups with more homogeneous difficulty *profiles* would probably pinpoint underlying causes and behavioral consequences more precisely, which would improve our overall understanding of dyscalculia.

However, it is very important that a resolution is reached in the research community, because such basic assumptions significantly impact both cognitive neuroscientific and behavioral research. Scientists that define dyscalculia differently and utilize different assessment methods choose different experimental populations and tasks. This leads to diverse experimental results and analyses that vary from researcher to researcher and may not be comparable to other experiments. This makes it very difficult to come to solid conclusions that will improve our understanding of dyscalculia. Instead, this experimental variability reinforces the existence of varying educational and cognitive neuroscientific perspectives like heterogeneity and competing developmental theories. If our knowledge of dyscalculia is to improve, it is *vital* that researchers adopt a uniform definition and explanation of dyscalculia. As it is, the use of so many variables complicate the already confusing mass of data, seriously affect our quality of knowledge, and slow progress on our understanding of dyscalculia.

Educational perspectives on the domain-specific and domain-general natures of dyscalculia

While there is good deal of disagreement regarding the neurological functioning, definition, characteristics and heterogeneity of dyscalculia, many of these seventeen articles referred to similar educational perspectives to explain how children learn and process mathematics. Specifically, there were two main types: perspectives relating to domain-specific processing mechanisms and perspectives relating to domain-general processing mechanisms. The educational theories relating to domain-specific processing mechanisms include the Numerosity Coding Hypothesis (NCH), the Approximate Number System (ANS), a deficit in magnitude representation, and the Access Deficit Hypothesis (ADH). Several articles also discussed the problem-solving strategies utilized by children with dyscalculia. The educational theories relating to domain-general processing mechanisms refer to non-mathematical cognitive mechanisms that children employ when mathematical tasks become difficult. Examples of these processing mechanisms include working memory, attention and executive functions. Since the focus of this paper is on perspectives related to numerical processing in children with dyscalculia, I will discuss domain-specific processing mechanisms first. Although I did not intend to write about domain-general processing mechanisms in this paper, they are relevant, and since most of the articles discussed them, a short discussion of how domain-general processing mechanisms affect children with dyscalculia will follow.

Table 9 summarizes the theories or perspectives identified in these seventeen articles. In all, there were seven articles that maintained that the sole fundamental deficit in dyscalculia was a deficit in magnitude representation. In addition, there was one article that argued solely for a deficit in numerosity, two articles that argued for deficits in both magnitude representation and numerosity, and one article that argued for deficits both in magnitude representation and in accessing the meaning of numerical symbols. Lastly, there were five articles that supported all three perspectives, and five articles that also discussed dyscalculic children's problem-solving strategy use. Eleven articles discussed the relationship between domain-general processing mechanisms and dyscalculia.

Table 9 also identifies the four review articles, the two sMRI research articles, and the eleven fMRI research articles. Of these eleven fMRI articles, six articles investigated children's abilities to compare symbolic and/or non-symbolic magnitudes, five articles investigated children's calculation skills, and one article investigated children's abilities in placing magnitudes on a number line.

Table 9. Perspectives addressed in the research articles on dyscalculia and cognitive neuroscience

Article	Research type	Research focus	Perspective on dyscalculia is related to D-S processes				Dyscalculia is related to D-G processes
Rosenberg-Lee et al., 2015	fMRI	Calc		MAGN	ADH	PSS	Compensatory mechanisms
Iuculano et al. (2015)	fMRI	Calc		MAGN			Compensatory mechanisms
Kucian & von Aster, 2015	Review		NUM	MAGN	ADH	PSS	Compensatory mechanisms
Kucian et al., 2014	sMRI		NUM	MAGN	ADH		
Ashkenazi, Rosenberg-Lee, Tenison, & Menon, 2012	fMRI	Calc	NUM	MAGN		PSS	D-G difficulties contribute
Kucian, Grond, et al., 2011	fMRI	NL	NUM	MAGN	ADH		Compensatory mechanisms
Butterworth et al., 2011	Review		NUM	MAGN	ADH		
Kucian, Loenneker, Martin, & von Aster, 2011	fMRI	NS		MAGN			Compensatory mechanisms
Kaufmann, Wood, Rubinsten, & Henik, 2011	Review		"Dysfunctional number system"				Compensatory mechanisms
Mussolin et al., 2010	fMRI	S		MAGN			
Kaufmann, Vogel, Starke, Kremser, & Schocke, 2009	fMRI	S & NS		MAGN			Compensatory mechanisms
Davis et al., 2009	fMRI	Calc		MAGN		PSS	Compensatory mechanisms
Kaufmann, Vogel, Starke, Kremser, Schocke, et al., 2009	fMRI	NS	NUM	MAGN		PSS	Compensatory mechanisms
Rubinsten & Henik, 2009	Review		NUM (pDD)	Causes vary for children with *cDD* and *MLD*			*MLD* are caused by D-G mechanisms
Rotzer et al., 2007	sMRI			MAGN			DD also have D-G processing deficits
Price, Holloway, Rasanen, Vesterinen, & Ansari, 2007	fMRI	NS		MAGN			
Kucian et al., 2006	fMRI	Calc & NS	NUM	MAGN	ADH		
Total number of articles			NUM: 8	MAGN: 15	ADH: 6	PSS: 5	D-G: 11

Perspectives addressed in the research articles on dyscalculia and cognitive neuroscience are highlighted in grey.
Column 2 identifies the article's research type (Review article, fMRI study or sMRI study). Column 3 identifies the research focus: Calculation skills (Calc), Number line (NL), Symbolic magnitude representation (S), and Non-Symbolic magnitude representation (NS).
Columns 4 – 8 identify which perspectives the articles adopted. Perspectives related to domain-specific (D-S) processing mechanisms include: the Numerosity Core Hypothesis (NUM), a deficit in magnitude representation (MAGN), the Access Deficit Hypothesis (ADH) and problem-solving strategy use (PSS). Perpectives related to domain-general (D-G) processing mechanisms include compensatory mechanisms, contributing mechanisms or additional deficits. White cells indicate that the article did not assert that the perspective was a main factor in dyscalculia.

In order to explain the mathematical deficits that children with dyscalculia have, all of the authors referred to educational theories related to domain-specific processing mechanisms. Approximately half of the articles identified a core deficit in numerosity as being one of the main difficulties for children with dyscalculia; however, the most common explanation of dyscalculia referred to by these articles was a deficit in the processing and representation of numerical magnitude. In fact, there were only two articles that did not refer to impaired magnitude representation in children with dyscalculia: Kaufmann et al. (2011) and Rosenberg-Lee et al. (2015), both of which are review articles. Kaufmann et al. (2011) mentioned difficulties in both numerosity and representations of numerical magnitude, but in their discussion, they proposed that children with dyscalculia have a "dysfunctional parietal number processing system". This was not clear enough to categorize this article.

Rubinsten and Henik (2009), on the other hand, was the only article whose arguments solely supported the Numerosity Core Hypothesis. In this article, they asserted that the core deficit in pDD was a difficulty in processing numerosities. However, the authors also maintained that dyscalculia was, in most cases, a heterogeneous disability: children with dyscalculia often had other comorbidities (cDD) and/or MLD. Rubinsten and Henik (2009) argued, therefore, that the deficits and difficulties experienced by children with dyscalculia varied greatly, depending on comorbid conditions, domain-general processing mechanisms and other factors. The authors' discussion on the homogeneity of dyscalculia also made it difficult to categorize this article.

However, all of the other fifteen articles argued that magnitude representation was significantly impaired in dyscalculic children, and seven[22] of these fifteen maintained that a deficit in magnitude representation was the core impairment in dyscalculia. Educational research has debated whether a deficit in magnitude representation involves non-symbolic or symbolic magnitudes. Butterworth (2010) criticized the ANS theory, arguing that approximate non-symbolic magnitudes cannot be used to solve arithmetic problems. The articles in this thesis seemed to support this argument, because of the six articles[23] researching magnitude representation, only one article identified a deficit in dyscalculic children's *non-symbolic* magnitude representation. Price et al. (2007) found that, when engaged in tasks

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[22] (Davis et al., 2009; Iuculano et al., 2015; Kaufmann, Vogel, Starke, Kremser, & Schocke, 2009; Kucian, Loenneker, et al., 2011; Mussolin et al., 2010; Price et al., 2007; Rotzer et al., 2007)

[23] (Kaufmann, Vogel, Starke, Kremser, & Schocke, 2009; Kaufmann, Vogel, Starke, Kremser, Schocke, et al., 2009; Kucian et al., 2006; Kucian, Loenneker, et al., 2011; Mussolin et al., 2010; Price et al., 2007)

comparing non-symbolic magnitudes, eleven-year-old children with dyscalculia used more time and made more errors than their non-dyscalculic peers. Price et al. (2007) posited that the neural circuitry supporting the fundamental representation of numerical magnitude in children with dyscalculia is impaired. Contrastingly, there were three articles that did not find any deficit in dyscalculic children's non-symbolic magnitude representation. Kaufmann, Vogel, Starke, Kremser, Schocke, et al. (2009), Kucian et al. (2006) and Kucian, Loenneker, et al. (2011) all found that children with dyscalculia performed equally well as their non-dyscalculic peers on tasks involving the comparison of non-symbolic magnitudes: children with dyscalculia were just as accurate, and used only marginally more time. In addition, when Mussolin et al. (2010) investigated dyscalculic children's *symbolic* magnitude representation, they found that children with dyscalculia made more errors and required more time than their non-dyscalculic peers when comparing symbolic magnitudes (Arabic numerals). On the other hand, the research of Kaufmann, Vogel, Starke, Kremser, and Schocke (2009) was contradictory to that of Mussolin et al. (2010). In their experiment, Kaufmann, Vogel, Starke, Kremser, and Schocke (2009) compared the behavioral performances of dyscalculic and non-dyscalculic children on two types of tasks: tasks involving the comparison of symbolic magnitudes, and tasks involving the comparison of non-symbolic magnitudes. Their research showed no difference in children's accuracy for either symbolic or non-symbolic magnitude representations. Contrastingly, the only behavioral difference Kaufmann, Vogel, Starke, Kremser, and Schocke (2009) found between children with and without dyscalculia was that children with dyscalculia used slightly more time on both comparison tasks.

Altogether, these results could be interpreted to discount the ANS theory, since the dyscalculic children in most of these studies performed equally well as their non-dyscalculic peers when making judgements on tasks comparing non-symbolic magnitudes. This analysis lends support to the assertion made by Butterworth (2010) that the ANS theory is incorrect. However, it must be noted that all of the participants in these studies were between the ages of eight and twelve years old. Geary (2015) questioned the applicability of the ANS model for children that have learned the foundational skills (i.e. number words and counting). By third grade, most children have learned elementary addition and subtraction, and have progressed past this developmental stage. If Geary's assertions are correct, the children in these six research studies would no longer struggle with the processing of non-symbolic magnitudes to the same extent that younger children do, so it would not be surprising that the researchers did not find a difference in children's non-symbolic magnitude representations. One article commented on exactly this: Mussolin et al. (2010) wrote that participants' ages play a crucial role, and referred to research that recorded a significant slowdown in the reaction rate of young children (aged 7-9 years). To further illustrate this contrast, Mussolin et al. referred to other experiments investigating magnitude representation that indicated that older children with dyscalculia did *not* perform more slowly than children without dyscalculia.

The fMRI results of these experiments also provide some evidence indicating that children with dyscalculia may not process magnitudes in the same way as their non-dyscalculic peers. Even though many of these studies did not show differences in the behavioral performance of children with dyscalculia, all of the articles identified differences in the brain activation patterns of children with dyscalculia as recorded by fMRI. This means that even if children with dyscalculia did not err more when comparing numerical magnitudes, their brains still processed magnitude comparisons differently than children without dyscalculia. Considering the ages of the participants, fMRI results and the limited number of studies, the ANS model cannot be discounted based on the articles in this literature review. Additional research on dyscalculia using younger children as participants is needed to investigate the applicability of the ANS model.

Another focus of these cognitive neuroscientific research articles involved the calculation skills of children with and without dyscalculia. Five articles investigated calculation skills: Iuculano et al. (2015), Rosenberg-Lee et al. (2015), Ashkenazi et al. (2012), Davis et al. (2009) and Kucian et al. (2006). Iuculano et al. (2015) investigated children's addition problem-solving skills before and after an eight-week intervention. They found that children with dyscalculia made more errors, and demonstrated increased brain activation compared to their peers in the control group. Rosenberg-Lee et al. (2015) identified both behavioral and neurocognitive differences between control children and children with dyscalculia, especially when the children engaged in solving *subtraction* problems. Ashkenazi et al. (2012) reported that the children with dyscalculia performed significantly worse on complex arithmetic problems and showed atypical brain activity in important regions for numerical processing. Davis et al. (2009), like Kucian et al. (2006), compared how children with and without dyscalculia engaged in tasks involving approximate and exact calculations. However, while Kucian et al. (2006) and Davis et al. (2009) used similar tasks, their results were dissimilar. Kucian et al. (2006) found no differences in behavioral performance for either exact or approximate calculation problems among children with and without dyscalculia – although they did record decreased brain activation patterns for dyscalculic children during the approximate calculation tasks. Davis et al. (2009), on the other hand, recorded *increased* brain activation patterns during *both* approximate and exact calculation. In addition, while Davis et al. (2009) reported similar accuracy rates between controls and dyscalculic children, the authors also reported that the children with dyscalculia needed significantly more time to solve each task.

However, as stated in the last section, Kucian's team combined the results from the nine and twelve-year-old children in their experiment, which may have muted their findings – since there were significant differences in performance between the nine and twelve-year old groups. Appendix A. contains a data table from the results section of Kucian et al. (2006)'s article, which shows that the nine-year-old children performed significantly worse than the twelve-year-old children, and the nine-year-old children with dyscalculia performed much worse than their non-dyscalculic peers on *both* the approximate *and* exact calculation tasks. For example, the data table shows that on average, the twelve-year-old *control* children scored correctly 87.9% of the time during the exact calculation tasks, while the twelve-year-old *dyscalculic* children scored correctly 84% of the time. During the same tasks, the nine-year-old *control* children scored correctly 73.7% of the time, whereas the nine-year-old *dyscalculic* children scored correctly 60% of the time. By combining the nine- and twelve-year-old's' test scores, the authors may have significantly underestimated the difference in performance between the nine-year-old dyscalculic and control test groups. Although Davis et al. (2009) and Kucian et al. (2006) used similar methods, Davis et al. (2009) chose only nine-year-old participants, and gave the children a fixed amount of time in which to answer. As a result, the results of Davis et al. (2009) and Kucian et al. (2006) varied significantly.

In contrast to the eight articles asserting that a deficit in magnitude representation was the main impairment in dyscalculia, there were seven articles[24] that maintained that children with dyscalculia have deficits *both* in magnitude representation and in processing numerosity. Kucian and von Aster (2015) reported that children with dyscalculia often have an impaired number sense, counting difficulties, and a reduced subsitizing range, as well as problems with estimating and comparing magnitudes. They explained that cognitive neuroscientific research showed that children with dyscalculia have aberrant brain activation patterns in neural regions presumed to be involved in numerical processing and that this is indicative of deficient

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[24] (Ashkenazi et al., 2012; Butterworth et al., 2011; Kaufmann, Vogel, Starke, Kremser, Schocke, et al., 2009; Kucian et al., 2014; Kucian, Grond, et al., 2011; Kucian et al., 2006; Kucian & von Aster, 2015)

representations of numerosity. Kucian et al. (2014), in their structural brain study, identified deficient fibre tracts connecting key brain regions responsible for the processing of numerical representation with other regions involved in the processing of numbers and in carrying out calculations. These deficient fibre tracts could affect a child's ability to process magnitudes, estimate quantities and have access to the mental number line (something which is hypothetically used for comparing magnitudes). Butterworth et al. (2011) maintains that the foundational deficit in dyscalculia involves a single core deficit in the understanding of sets and numerosities, which is fundamental for the comparing and representation of numerical magnitudes. In addition, Butterworth et al. (2011) wrote that children with dyscalculia have difficulties with enumeration and that they lack an understanding of numbers and judgements of magnitudes. Ashkenazi et al. (2012) listed the same difficulties, arguing that children's impaired numerical representation and magnitude processing, as well as deficient counting skills, lead to difficulties in acquiring higher level mathematical skills.

Cognitive neuroscience and the Access Deficit Hypothesis

The third educational perspective identified in these articles is the Access Deficit Hypothesis. Six articles[25] referred to this perspective, arguing that difficulty in encoding numerical symbols is one of the main deficits in dyscalculia. Rosenberg-Lee et al. (2015) wrote that children with dyscalculia have persistent difficulties in connecting the meaning of numerical magnitudes with number words and Arabic numerals. Butterworth et al. (2011) wrote that recent research "is providing a scientific characterization of dyscalculia as a reduced ability for understanding numerosities and mapping number symbols to number magnitudes". Furthermore, the work of Kucian et al. (2014) and Kucian and von Aster (2015) asserted that there was a disconnect between magnitudes and numerical symbols in children with dyscalculia, and Kucian, Grond, et al. (2011) posited that the development of a symbolic number system augmented the child's magnitude representation. This means that deficits in connecting number symbols to magnitudes, coupled with an already impaired magnitude representation, numerical understanding and counting skills creates severe difficulties for children with dyscalculia. In addition, Kucian et al. (2014) and Kucian and von Aster (2015) argue that this difficulty in connecting magnitudes with their numerical symbols also affects

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[25] (Butterworth et al., 2011; Kucian et al., 2014; Kucian, Grond, et al., 2011; Kucian et al., 2006; Kucian & von Aster, 2015; Rosenberg-Lee et al., 2015)

the child's ability to *transform* numerical representations - in other words, making the acquisition and comprehension of calculation skills difficult.

Cognitive neuroscience and dyscalculic children's problem-solving strategies

If, as these authors argue, dyscalculic children's deficits in accessing the meaning of and transforming quantities and their numerical symbols is accurate, it could explain the difficulties children with dyscalculia exhibit in learning effective problem-solving strategies. Of the seventeen articles, five[26] referred to the problem-solving strategies utilized by children with dyscalculia. Kucian and von Aster (2015) wrote that while children with a typical mathematical development initially solve arithmetic problems using inefficient counting strategies, they eventually automatize number facts and learn to use this knowledge to choose more effective retrieval strategies. However, children with dyscalculia have difficulty in internalizing arithmetic facts, and lack an understanding of calculation concepts and procedures. This leaves dyscalculic children unable to use retrieval strategies such as fact decomposition, and results in a dependence on basic finger-counting strategies. This reliance on basic counting strategies was reported in Kaufmann, Vogel, Starke, Kremser, Schocke, et al. (2009), as the authors identified increased brain activation in dyscalculic children as the children engaged in simple tasks comparing non-symbolic magnitudes (comparing images of fingers). In their discussion, the authors surmised that instead of subsitizing, the children were continuing to rely on counting strategies.

This reliance on counting strategies was also documented in Ashkenazi et al. (2012), Davis et al. (2009) and Rosenberg-Lee et al. (2015), who investigated dyscalculic children's choice of arithmetic problem-solving strategies. These authors referred to David Geary's research involving back-up and retrieval strategies, analyzing their results in light of this perspective. Ashkenazi et al. (2012, p.164) wrote that, according to their experimental results, "arithmetic fact retrieval is one of the most pronounced deficits in children with DD". The findings of Davis et al. (2009) also supported a deficit in problem solving. Davis et al. (2009, p. 2475) wrote: "our findings are consistent with the evidence that children with MD employ the same types of strategies as TD[27] children but use more developmentally immature and less efficient forms of these strategies". Furthermore, Rosenberg-Lee et al. (2015) found that children with

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[26] (Ashkenazi et al., 2012; Davis et al., 2009; Kaufmann, Vogel, Starke, Kremser, Schocke, et al., 2009; Kucian & von Aster, 2015; Rosenberg-Lee et al., 2015)

[27] «TD» refers to children with a typical mathematical development, while «MD» refers to children with Mathematical Disability».

dyscalculia were slower and less accurate when solving both addition and subtraction problems than the children in the control group. However, they also noted that dyscalculic children were especially impaired when solving subtraction problems, which they proposed was “due to the use of slower and more effortful counting strategies, contrasted with direct retrieval of the answer”. In addition, the authors asserted that their fMRI data supported this: they found that the brain activation patterns of children with dyscalculia were most affected when solving subtraction problems. Rosenberg-Lee et al. (2015) reasoned that this increase in brain activation was due to the children’s need for additional neural resources, and the authors concluded that subtraction was much harder for children with dyscalculia.

Domain-general processing mechanisms in children with dyscalculia

While all seventeen articles described the core deficits involved in dyscalculia by referring to domain-specific learning mechanisms, more than half of the articles argued that domain-general processing mechanisms were also relevant. Eleven[28] articles claimed that children with dyscalculia engage domain-general learning mechanisms when manipulating numbers or comparing numerical magnitudes. Of these eleven articles, nine[29] presented fMRI results indicating that children with dyscalculia show increased involvement in their brains’ frontal regions, which are presumed to regulate domain-general processes like attention and working memory. These articles concluded that increased activation in domain-general brain regions reflected effortful processing demands and suggest that the numerical deficits of children with dyscalculia require extra resources in order to compensate. Rosenberg-Lee et al. (2015) wrote about exactly this: they identified a “hyperconnectivity” in frontal regions of dyscalculic children’s brains, which the authors pointed out as being part of a network that played an important role in the attention and working memory processes required for problem solving. Furthermore, the authors maintained that the activation of these neural networks reflected the engagement of “prefrontal compensatory systems.” Davis et al. (2009) asserted that increased activation of these neural regions indicated greater cognitive demands: the children needed to compensate for their reliance on primitive problem-solving strategies – strategies that have been shown to require more working memory and attentional resources. Kucian, Grond, et al.

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[28] (Ashkenazi et al., 2012; Davis et al., 2009; Iuculano et al., 2015; Kaufmann, Vogel, Starke, Kremser, & Schocke, 2009; Kaufmann, Vogel, Starke, Kremser, Schocke, et al., 2009; Kaufmann et al., 2011; Kucian, Grond, et al., 2011; Kucian, Loenneker, et al., 2011; Kucian & von Aster, 2015; Rosenberg-Lee et al., 2015; Rotzer et al., 2007)

[29] (Davis et al., 2009; Iuculano et al., 2015; Kaufmann, Vogel, Starke, Kremser, & Schocke, 2009; Kaufmann, Vogel, Starke, Kremser, Schocke, et al., 2009; Kaufmann et al., 2011; Kucian, Grond, et al., 2011; Kucian, Loenneker, et al., 2011; Kucian & von Aster, 2015; Rosenberg-Lee et al., 2015)

(2011) and Kaufmann, Vogel, Starke, Kremser, Schocke, et al. (2009) also wrote about dyscalculic children's use of domain-general processing mechanisms to compensate for their numerical deficits. Kucian, Grond, et al. (2011, p. 792) wrote: "Our results lend further support to a deficiency in numerical representation in the parietal lobe associated with dyscalculia, causing stronger engagement of supporting frontal lobe functions such as working memory and attentional control to solve a numerical task." Kaufmann, Vogel, Starke, Kremser, Schocke, et al. (2009) explained that as a result of their dependence on complicated compensatory strategies, children with dyscalculia are very dependent on working memory and executive functions, as indicated by frontal lobe engagement. These authors also explained that this overloading of cognitive working processes causes dyscalculic children to require more time to solve problems, and leads to more inaccuracy in their work.

Only Ashkenazi et al. (2012) and Rotzer et al. (2007) held differing opinions regarding dyscalculic children's use of domain-general processing mechanisms when processing numerical information. Ashkenazi et al. (2012, p. 163) wrote[30] that "central executive and working memory deficits are known to be important factors contributing to poor problem solving and fact retrieval in children with DD." As a result of this assumption, Ashkenazi et al. (2012) included children with weak visuo-spatial working memory (VSWM) capacities in their dyscalculic group - while the children in their control group had no such deficits. It is thus not surprising that Ashkenazi et al. (2012) identified atypical brain activation patterns in regions presumed to be responsible for VSWM in their experimental group of dyscalculic children. Rotzer et al. (2007, p. 420), referring to one publication[31] from 1989, wrote that it was a "fact that children with arithmetical disability have a specific working-memory deficit". Afterwards, in their discussion, the authors argued that this working memory (WM) impairment "might have a negative effect on the acquisition of number representation and number processing capacities". While their inference that an impairment in working memory could cause difficulties in acquiring mathematical knowledge is sound, assumptions that children with dyscalculia have a WM or VSWM impairment is not widely supported.

Instead, the dominating opinion in these articles is that dyscalculia is not caused by domain-general processing mechanisms. For example, Rubinsten and Henik (2009) argued that pDD is founded in a deficit in core numerical abilities and the processing of quantities, and that

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[30] Referring to Rotzer et al. (2009), Geary (2004) and Geary, Hoard, Byrd-Craven, Nugent, and Numtee (2007)
[31] (Siegel & Ryan, 1989)

difficulties in other cognitive domains are not causes of pDD, but rather are secondary, or additional learning difficulties. However, the authors also pointed out that impairments in domain-general processing mechanisms and comorbid conditions would contribute to the difficulties children with dyscalculia have in acquiring numerical information and skills. Butterworth et al. (2011) addressed this as well, writing that “arithmetic competence involves a wide range of cognitive skills, impairments in any of which may affect performance, including reasoning, working memory, language understanding and spatial cognition.” However, Butterworth et al. (2011) also pointed out that when learning new arithmetic facts, children primarily activated frontal regions of the brain. With repeated numerical experiences, numerical information becomes automatized and brain activity shifts from frontal regions to parietal areas (associated with magnitude processing and fact retrieval). This is why research on domain-general processing mechanisms is also important and relevant for research on dyscalculia: children with dyscalculia rely on these processing mechanisms in order to compensate for their numerical deficits. It is important that we understand that these children are not “stupid” or “slow”, but that they struggle because of their numerical processing deficits – and are reliant on domain-general processing mechanisms to compensate for their poor numerical understanding and choice of resource-demanding problem-solving strategies. It is important to understand why these children utilize such effortful strategies, how these cognitive processes work, and how to best help dyscalculic children acquire new numerical knowledge and learn new and less cognitively-demanding strategies.

According to this analysis, the majority of these seventeen articles supported deficits in domain-specific processing mechanisms as being central to dyscalculia – specifically, an impairment in symbolic magnitude representation. In addition, numerous articles attested that a deficit in accessing the meaning of numerical symbols is a main characteristic of dyscalculia, while no articles discounted the ADH theory. Rather, acquired knowledge of numerical symbols was reported to augment children’s magnitude representations, tying together these two theories. Half of the articles also argued that an impairment in numerosity is a defining feature of dyscalculia: because children with dyscalculia lack an intrinsic understanding of number and fail to acquire the understanding that numerical magnitudes can be decomposed into various number sets. The relationship between these theories and children’s choice of problem-solving strategies was also discussed.

So, while these various educational theories are debated, and at times even seem to contradict one another in pedagogical literature, the results of this analysis suggest that numerical magnitude, numerosity and access to the meanings of numerical symbols are inextricably linked. Children that lack knowledge of numerical magnitudes will also find it difficult to acquire an understanding of, and make connections between, number concepts and sets. These children, lacking an understanding of the meanings of numbers and how they are composed, are unable to connect these number meanings to their symbolic representations, and therefore have difficulty manipulating these symbols and calculating arithmetic problems, as calculation procedures also lack meaning. Instead, these children must rely on primitive back-up strategies to calculate the answers to arithmetic problems. Larger numbers and increasingly complex arithmetic problems put a strain on dyscalculic children, requiring more effort, energy and memory resources to solve these arithmetic problems, while their peers take advantage of the shortcuts, decomposition and retrieval methods that they have learned to more efficiently solve these same problems. It is no wonder that, as Ostad's research showed, the mathematical development of dyscalculic children seems to stagnate at a second-grade level (Ostad, 2010, 2013). Without gaining a foundational understanding of numerical magnitude and numerosity, dyscalculic children will continue to struggle with the meanings of numerical symbols and abilities to transform these numbers when solving arithmetic problems.

Summary of part one

In this chapter, I presented and discussed results from this literature review in order to answer my first question, "*What does recent research on cognitive neuroscience have to say about dyscalculia?"* Here, I presented patterns identified in my corpus of articles, including perspectives related to cognitive neuroscience, like the localization, network and connectivity models, brain activation patterns, and dyscalculia as a heterogeneous or homogeneous disability. My analysis indicated changing views regarding the localization of cognitive processing mechanisms, and the importance of seeing numerical processing as taking place in interconnected networks: where both loci and connectivity are important. Over time, cognitive neuroscience has acknowledged that dyscalculia is not necessarily due to defective brain tissue or an impaired activation of neural resources, but that children with dyscalculia may also show *increased* neural engagement. Perspectives related to educational research can add meaning to cognitive neuroscientific research results – like how increased brain activation in frontal areas can be indicative of children's use of compensatory strategies. Cognitive neuroscientific research can also give support to educational perspectives and researchers like Ostad and Geary, who wrote about dyscalculic children's cognitively-demanding problem-solving strategies. Understanding the mechanisms of children's neural processing can add positivity to a difficult situation and help to change general attitudes – communicating that children with dyscalculia are not stupid or slow (as they are sometimes led to believe), but rather that they have different ways of processing numerical information.

I also explored the authors' perspectives on the heterogeneity or homogeneity of dyscalculia and the major impact these perspectives have on dyscalculia research – as they greatly affect the researchers' criteria for their experimental populations, choice of experimental tasks and analysis. In addition, because the results of these experiments also add to the confusion and debate surrounding dyscalculia. The fact that scientists have used such different definitions and diagnostic criteria has resulted in a multitude of explanations and perspectives related to dyscalculia – which has not made it easier for children with dyscalculia to receive the help that they need. Rather, increased knowledge should *add* to our competence: help us to define, explain and remediate dyscalculia – like it has done with dyslexia. Instead, the fact that there are so many perspectives around dyscalculia and approaches for studying it, has not improved our ability to come to a consensus regarding what dyscalculia is, what causes it, or how to help. Rather, what we have is a fragmented picture of dyscalculia, surrounded by many theories, but not enough research to establish a firm foundation for remediation.

In the last section of part one, I presented educational perspectives identified in these articles, including perspectives related to domain-specific processing mechanisms, like magnitude representation, the ANS, the NCH, the ADH and problem-solving strategies. In this section, I also discussed how the authors of these seventeen articles viewed domain-general processing mechanisms and their relationship with domain-specific processing mechanisms. The consensus of these articles was that dyscalculia was due to impairments in domain-specific processing mechanisms (i.e. deficits in magnitude representation, numerosity and accessing numerical symbols). However, most of these articles also argued that domain-general processing mechanisms were relevant and could affect numerical processing. In particular, the engagement of domain-general processing mechanisms is related to the resource-demanding, primitive, back-up strategies utilized by dyscalculic children. This section concluded by discussing how cognitive neuroscientific perspectives can inform and tie together educational perspectives. Doing so can help to identify important concepts and foundational skills that dyscalculic children must acquire if their mathematical understanding is to improve. In the next part of this paper, I will present the interventions for the remediation of dyscalculia that were identified by these articles. I will also discuss the relationship these foundational skills and concepts have to the remediation of dyscalculia.

Part two: Neurocognitive research on interventions for remediating dyscalculia

While there have been numerous behavioral studies investigating interventions for remediating dyscalculia, very little research has been done to investigate the neurological effects these interventions have on the dyscalculic brain. Of the initial 213 articles that I sifted through, there were only *two* fMRI research articles that investigated the neurological effects interventions have on the dyscalculic brain. Two fMRI studies are a very small sample set, but the results so far are inspiring.

In this section, I will present and discuss articles that relate to my second research question, “What does neurological research on dyscalculia say about the effect of interventions on children’s learning?” Of the seventeen articles on neurocognitive research and dyscalculia, *four* articles discussed or investigated interventions for the remediation of dyscalculia. Two articles, Kucian, Grond, et al. (2011) and Iuculano et al. (2015) utilized fMRI to study the neurological effects numerical training programs had on the dyscalculic brain. The other two articles, Butterworth et al. (2011) and Kucian and von Aster (2015), are review articles of neurocognitive research on dyscalculia, and both articles presented research and discussed issues and research related to the diagnosis of, and interventions for remediating dyscalculia. These articles are summarized in table 10.

Table 10. Articles addressing mathematical interventions for children with dyscalculia

Article	Summary
Iuculano et al. (2015)	FMRI experiment comparing the brain activation patterns of children with and without dyscalculia before and after participating in an eight-week, instructor-led, tutoring program.
Kucian & von Aster, 2015	Discusses the mathematical and neurological development of children with dyscalculia, and factors related to diagnosis and intervention.
Kucian, Grond, et al., 2011	FMRI experiment comparing the brain activation patterns of children with and without dyscalculia before and after a 5-week intervention using a computer-based tutoring program.
Butterworth et al., 2011	Presents a model of dyscalculia from a behavioral and cognitive neurological standpoint, and discusses implications for diagnosis and intervention.

Kucian, Grond, et al. (2011) compared the behavioral performance and brain activation patterns of children with and without dyscalculia before and after participating in a computer-based training program. This computer program, *Rescue Calcularis,* was designed to train children's concept of ordinality by strengthening the link between their numerical representation and the number line. The computer program trained children at their own pace, automatically adjusting the difficulty of numerical tasks to fit the individual child's needs. The children's numerical abilities were assessed both before and after the five-week intervention period, and they also underwent fMRI before and after participating in the training. In addition, half of the dyscalculic children underwent a third fMRI session five weeks after completing the program.

Behavioral results of the intervention showed that both the control and experimental groups had an improvement in accuracy and numerical understanding. However, the children with dyscalculia showed the most growth in their mathematical skills. In addition, fMRI identified neurological changes in brain activation patterns for both the control and experimental groups. Prior to training, dyscalculic children showed less brain activation in their parietal regions compared to the control children, but stronger activation in their frontal lobes. The authors attributed this as being due to the compensatory processing mechanisms that the children engaged to solve the numerical tasks. However, after training, *both* groups showed a clear reduction in the recruitment of relevant neural regions. Kucian, Grond, et al. (2011) suggested that this decrease in activation indicated that the children, through practice, had automatized these numerical skills, resulting in less demand on supportive domain-general processing mechanisms. Surprisingly, fMRI post-training did not indicate any *increase* in brain activation in the parietal regions responsible for numerical reasoning - for *either* the control or experimental groups. Five weeks later, a group of six dyscalculic children underwent a third fMRI session. Interestingly, this additional fMRI session identified greater recruitment of the children's IPS, even though during these five weeks, the children did not use the training software. Kucian, Grond, et al. (2011) proposed that this increase in brain activation in domain-specific regions was due to a reorganization and incorporation of the acquired numerical skills into long-term memory storage – and the authors posited that this consolodation required additional time. Furthermore, Kucian and colleagues concluded that while both groups showed an improvement, both neurologically and behaviorally, the children with dyscalculia showed a greater benefit from the intervention - as well as a "partial remediation of deficient brain activation in dyscalculics after consolidation of acquired and refined number representation" (Kucian, Grond, et al. 2011, p.793).

The other article by Iuculano et al. (2015) also reported positive effects of intervention. In their experiment, Iuculano et al. investigated the behavioral and neurological results of an intensive, eight-week, 1:1 tutoring program focusing on conceptual aspects of number and number fact training. The intervention was adapted from the highly systematic tutoring program "Mathwise", which was designed to stregthen children's knowledge of number properties and relationships between arithmetic operations. In addition, the training aimed to increase children's use of more efficient problem-solving strategies and knowledge of number families. In the intervention, lessons were led by a trained instructor, and children in both the control and dyscalculic groups engaged in two fMRI sessons: one before the intervention, and one session after. The behavioral results for the children with dyscalculia showed an increase in accuracy for arithmetic problem solving, to the extent that the dyscalculic children's accuracy levels no longer differed statistically from that of their typically-developing peers. Reaction times, however, were not reduced in the dyscalculic group. As for the children without dyscalculia, their problem-solving accuracy rate did not improve statistically, although their reaction time did decrease significantly.

Iuculano et al. (2015) also recorded neurological changes which the authors presumed to be a result of the training program. Before the intervention, the dyscalculic group showed "differential and widespread overactivation in multiple neurocognitive systems, likely reflecting the need for greater neural resources during arithmetic problem solving". In comparison, the control group showed activation in similar brain regions as the dyscalculic group, although their brain activation patterns were reduced and tended to be more focused in particular brain regions. However, after eight weeks of tutoring, fMRI no longer indicated this overaction in dyscalculic children's brains. Instead, fMRI identified reduced brain activation patterns in *all* neural networks for the children with dyscalculia. In orther words, the brain activation patterns in the dyscalculic group after tutoring were not statistically distinguishable from the brain activation patterns of their non-dyscalculic peers. Iuculano et al. (2015) concluded that a comprehensive tutoring program not only can successfully remediate poor numerical skills among children with dyscalculia, but can even normalize children's brain activation patterns to the extent that the dyscalculic children's brain activation patterns no longer differed from those of their normally-developing peers.

The other two articles, Butterworth et al. (2011) and Kucian and von Aster (2015) reviewed cognitive neuroscientific research discussing the diagnosis of dyscalculia and interventions for remediation. Butterworth et al. (2011) presented essential aspects that must be considered when designing remediation plans for children with dyscalculia, as well as important components of intervention programs. They explained that neural specialization develops through an interaction between the brain and a child's learning experiences. Furthermore, Butterworth et al. (2011, p. 1050) wrote that "one way of thinking about dyscalculia is that the typical school environment does not provide the right kind of experiences to enable the dyscalculic brain to develop normally to learn arithmetic." Many schools remediate mathematics by targeting gaps in a child's knowledge base and seeking to fill these gaps. However, Butterworth et al. pointed out that this is often ineffective because interventions that seek to fill gaps in children's learning do not address dyscalculia's underlying problems, specifically, children's deficits in numerical magnitude, numerosity and numerical representations. Instead, Butterworth et al. (2011, p. 1051) wrote that neuroscientific research has indicated that "rather than address isolated conceptual gaps, remediation should build the foundational number concepts first." To illustrate this from a cognitive neuroscientific standpoint, *both* Butterworth et al. (2011) and Kucian and von Aster (2015) cited research indicating that the parietal lobes are activated *whenever* numerical magnitude is implicated – even when the numerical task involves simple, automatized arithmetic problems. Furthermore, Butterworth et al. (2011) explained that if the link for the *meanings* of component numbers has not been established, then calculation is impaired. Therefore, the authors argued that it is essential that interventions strengthen the meaningfulness of numbers, especially the relationships between number facts and their meanings.

Manipulatives are one tool that teachers use to assist children in making connections with numbers in ways that the children can relate to. For example, special education teachers often use Cuisinaire rods, activities and games to help children learn about number meanings and relationships. However, Butterworth et al. (2011) pointed out that interventions involving specialized teachers (or specially-trained assistants) are very resource-demanding – and are not something that schools are able to afford on a regular basis. An alternative option, Butterworth and colleagues proposed, was to supplement lessons with computer programs. The authors explained that this type of intervention "has the potential to reduce the demand on specially trained teachers and to transcend the limits of the school schedule."

Butterworth et al. (2011) reviewed three programs with adaptive software based on neuroscientific research: *The number race, Graphogame maths* and the *Number bonds* game. *The number race* was designed to improve children's magnitude representations by training the child's non-symbolic comparison skills. *Graphogame maths* also trained children's non-symbolic comparison skills in order to improve children's numerical representation and their understanding of numerical sets. However, *Graphogame maths* differed from *the number race* in that *Graphogame maths* used smaller magnitudes. Smaller magnitudes made it easier for the child to count and match the magnitudes with their numerical symbols, thereby assisting the link between the number's representation and the number of objects in its set. For this reason, *Graphogame maths* was the more effective of these two programs in the learning of number comparisons. However, Butterworth et al. (2011) also pointed out that this research did not indicate that these children's improved magnitude comparison skills led to better counting, knowledge of number relationships or arithmetic skills – because neither game required the children to manipulate numerical quantities. According to the arguments made by Geary (2015) and Butterworth (2010) questioning whether the ANS theory was relevant for school-age children who had already acquired the foundational knowledge of non-symbolic magnitude comparisons, a successful intervention program should instead train children's skills in their manipulation of numerical quantities. In Butterworth et al. (2011, p. 1052), the authors asserted that "manipulation is critical for providing an intrinsic relationship between task goals, a learner's actions, and informational feedback on those actions." By receiving informational feedback from the program, children can interpret for themselves what an improved response would be, causing the children to become their own critics, and lessoning the demand for the teacher's guidance.

The third computer program that Butterworth et al. (2011) reviewed was the *Number Bonds* game. This software was also based on neuroscientific research, and emulated the activities special educators use with Cuisinaire rods. The adaptive software in the game aimed to improve children's numerosity processing. To do this, the game began with images of manipulatives similar to the ones used in schools, and gradually progressed to abstract numerical symbols. In this way, children manipulated the magnitudes and worked on connecting the relationships between the numerical quantities and their numerical representation. According to the Access Deficit Hypothesis, this link is essential in order to give meaning to numerical symbols.

The fourth article, Kucian and von Aster (2015), cited a meta-analysis[32] by Ise & Schulte-Körne which identified six important aspects of a successful intervention:

1.) Intervention has a 1:1 student to teacher ratio
2.) Intervention is adapted to the individual child's performance level
3.) Intervention is systematic and has a hierarchical structure
4.) Intervention includes both foundational and curricular topics
5.) Intervention consists of many repetitions
6.) The child's motivation is stimulated with rewards and a reduction of anxiety levels.

Kucian and von Aster (2015) applied these six points to explain how adaptive software like their program *Calcularis* could be a valuable addition to an intervention program - particularly because children enjoy playing computer games, and because anxiety due to social pressure is often reduced in such settings. *Calcularis* is an updated version of the adaptive software *Rescue Calcularis,* which was used in the experiment by Kucian, Grond, et al. (2011). Kucian and von Aster (2015) reported that their newer version, *Calcularis*, is also based on "current neurocognitive models of numerical cognition", and wrote that this program was extended to include numerous games which were structured in a hierarchical fashion. In addition, the software adapted to the responses of individual learners, training many numerical and arithmetic aspects, including: subsitizing, non-symbolic magnitude and size comparisons, properties of numbers and counting, number line comprehension, the four arithmetic operations, and transcoding between number words, magnitudes and Arabic digits. Kucian and von Aster (2015) reported positive improvements in children's arithmetic skills, problem solving strategy use, and mathematical comprehension after using this program for six or twelve weeks.

In conclusion, Kucian and von Aster (2015) wrote that interventions can be helpful tools in the remediation of dyscalculic children's mathematical understanding and performance when they were carefully adapted to the individual child's learning profile and were based on current neurocognitive research. However, Kucian and von Aster (2015) and Kucian, Grond, et al. (2011) were careful to note that computer programs were not a substitute for quality intervention programs involving structured, individual lessons with a trained educator. Rather, Kucian and von Aster (2015, p, 10) wrote that computer programs like *Calcularis* should be

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[32] Ise, E., & Schulte-Körne, G. (2013). Symptomatik, DIagnostik und Behandlung der Rechenstörung. Zeitschrift für Kinder- und Jugendpsychiatre und Psychotherapie, 41(4), 271-282.

used to supplement quality tutoring, “since individual therapy by trained dyscalculia therapists seems still more effective”.

Another factor related to interventions of the remediation of dyscalculia involve the diagnostic process. Butterworth et al. (2011) argued that since comorbidity was common among children with dyscalculia, it was important to differentiate dyscalculia from other causes of low numeracy. In order to do this, the authors suggested that diagnostic materials testing the enumeration and comparison of sets supplement the existing diagnostic tests. Kucian and von Aster (2015) referred to dyscalculic children’s heterogeneous learning profiles and pointed out that children with dyscalculia often have additional learning difficulties – and could also develop psychiatric disorders or problematic behavior, which could lead to extra difficulties in learning mathematics. Thus, the authors maintained that the diagnosis of dyscalculia should be “based on multidimensional assessments tracking different numerical and arithmetical processes and relevant domain general abilities as well as neurological and socioemotional functions.” Furthermore, Kucian and von Aster (2015) wrote that in order to develop an intervention plan addressing all of the child’s needs, strengths and weaknesses, detailed diagnostic evaluations like this are vital to provide an accurate picture of the child. This means that in order to design and appropriate intervention, professionals must first take into consideration all aspects of the child’s life, including: mathematical and academic development, cognitive processing abilities, social factors, personal and familial history, emotional well-being, and, when available, findings from neuropsychological evaluations.

In this section, I discussed my second question, “What does neurological research on dyscalculia say about the effect of interventions on children’s learning?” The cognitive neuroscientific articles presented two types of interventions for the remediation of dyscalculia: adaptive software programs to support instruction, and intensive individual tutoring programs with trained instructors. The authors emphasized that interventions should be based on neurocognitive research and include foundational concepts of numbers and mathematics. Interventions should also be adapted to the child’s individual needs and progress at the child’s own pace. So far, the research that has been carried out has indicated that interventions can lead to improvements in dyscalculic children’s numerical abilities as well as a reorganization of children’s neural physiology. This data was only based on a few fMRI studies, but the idea that children with dyscalculia can show such remarkable brain plasticity is inspiring and gives hope to the many children struggling with mathematics.

The discovery of Kucian, Grond, et al. (2011) implies that fMRI research on interventions for the remediation of dyscalculia should implement rest periods before fMRI sessions are undertaken subsequent to training programs, since the child's brain may need time to consolidate or reorganize their acquired knowledge into long-term memory. Longitudinal research also needs to be conducted to evaluate the long-term effects of interventions and whether the child is able to apply the acquired knowledge to other aspects of mathematics.

It is unfortunately too early to say with any certainty what effect interventions have in remediating dyscalculia, considering the scarcity of neurocognitive research on the topic. In addition, the authors' different definitions of dyscalculia, as well as the resulting criteria for their choice of research populations - and their experimental methods - greatly affect the results of neurocognitive (and educational) research. For example, Iuculano et al. (2015) included in their dyscalculic group children that scored in the lowest 16% on an assessment test - which does not match the expected prevalence rate supported by most researchers. This means that it is possible that not all of the children in Iuculano et al. (2015) 's experimental group had dyscalculia. This is a potential problem because if some of the children had other causes for their poor mathematical performance, combining their brain activation data with the true dyscalculics would have weakened the fMRI data and make it difficult to make inferences about dyscalculic children's brain plasticity.

Several important points regarding interventions for the remediation of dyscalculia were made in these articles which need to be taken into consideration when designing intervention plans. First, interventions must be developed according to the child's specific needs: including the child's diagnoses, strengths, weaknesses, history and interests. In addition, it is important to be aware of prior efforts at remediation, consideration being given to the remediation's successes and failures to ensure that unsuccessful methods are not repeated. Instead, the intervention should provide positive experiences for the child such that he learns that mathematics can be enjoyable, that he can succeed in his mathematical pursuits, and to give him hope that he can improve his mathematical knowledge and skills. Experiencing success as a result of his efforts, and participating in positive and enjoyable mathematical activities, can lead to an increase in the child's motivation to engage in mathematical tasks and activities and a decrease in potential problematic behaviors. Kucian, Grond, et al. (2011) and Kucian and von Aster (2015) pointed out that interventions can use games to make learning mathematics fun and interesting, but at the same time, they must have a pedagogical focus that is supported by neurocognitive research. This means that interventions for the remediation of dyscalculia should address foundational numerical skills and concepts, and not just isolated gaps in the child's mathematical knowledge – which is a common practice in schools when children are receiving extra help with class assignments. Interventions should include meaningful tasks to strengthen the child's understanding of numerical magnitude, the relationship between numbers and how they are composed, and these interventions should also help the child to connect magnitude representations with their representative numerical symbols. In addition, intervention plans should aim to improve children's use of effective problem-solving strategies, train the child's knowledge of number facts, and develop his understanding of the relationships between arithmetic operations. At the same time, interventions should include some mathematical topics from class, so that the child can experience success in the classroom as well.

One topic that was not raised by these articles was the inclusion of children's caregivers. It is vital that parents are included in discussions surrounding the child's needs and the design of interventions. One reason for this is that parents are generally keen to help in any way that they can, and by educating them in the instructional methods used in the intervention, they can support the child's learning at home. Families can also give insight into the child's interests and suggest topics or methods that might motivate the child.

6 Conclusion

Even though cognitive neuroscientific research on dyscalculia is still quite a relatively new research area, recent experimental results have provided some inspiring possibilities that can provide hope to the many children and families that struggle with this learning disability on a daily basis. Cognitive neuroscience can also offer insight to school professionals who are searching for answers as to what dyscalculia is, and what types of interventions can successfully remediate children's mathematical difficulties.

However, it is still unclear as to how much children with dyscalculia can improve as a result of intervention, whether this change is permanent and whether children's acquired knowledge is transferable to new and more complex numerical tasks. This brings to mind the question of whether dyscalculia is a lifelong disability like dyslexia, as many researchers propose – or if with proper intervention, children's cognitive processing of numerical information can be improved – or even normalized. While neuroscience *has* recently indicated that the human brain is remarkably flexible, the answers to these questions remain unanswered, and await additional research.

In this thesis, I have sought to answer two questions about dyscalculia and cognitive neuroscience by conducting a systematic literature review of neurocognitive research. To answer my first question, "What does recent research on cognitive neuroscience have to say about dyscalculia?", I defined dyscalculia and presented characteristics and educational theories explaining how we develop numerical knowledge and some reasons children struggle with mathematics. The next step in my systematic literature review was to conduct a literature search and analyze the resulting articles, from which three important topics emerged.

First, cognitive neuroscience explains dyscalculia as a mathematical disability due to a dysfunction of domain-specific processing mechanisms in various brain locations. Contrary to earlier views, research has indicated that numerical processing occurs within connected networks involving both domain-specific and domain-general processing mechanisms. Children with dyscalculia show deficits in numerical processing and fMRI has identified increased brain activation patterns in children's frontal lobes, indicating strong demands on supportive cognitive processing mechanisms. Cognitive neuroscientists have interpreted this to mean that children with dyscalculia compensate for their numerical deficits by recruiting extra frontal resources like attention and working memory.

Second, my analysis identified major conflicts between and within research communities that hinder the advancement of our knowledge on dyscalculia. In particular, neuroscientific and educational researchers debate the heterogeneity of dyscalculia. As a result of their diverse definitions and diagnostic criteria for dyscalculia, their choice of experimental populations and methods differ widely. This causes experimental results and researchers' conclusions to vary widely, which is detrimental to our understanding of this learning disability.

At the same time, these articles shared similar educational perspectives explaining the numerical difficulties experienced by children with dyscalculia. First, dyscalculia seems to be due to deficits in children's magnitude representation and understanding of quantities and how they are made up. Many researchers also acknowledge that dyscalculic children show great difficulty in connecting the meaning of numerical symbols to their respective magnitudes and that this affects children's abilities to solve arithmetic problems. In addition, multiple articles also confirmed existing behavioral research describing dyscalculic children's poor choice of problem-solving strategies. Neurocognitive research indicated increased dependence on executive function, working memory and attentional resources in order to compensate for these children's numerical difficulties.

My second research question, "What does neurological research on dyscalculia say about the effect of interventions on children's learning?" was answered by reviewing four articles that presented and discussed neurocognitive research on interventions for the remediation of dyscalculia. These articles presented two types of interventions: adaptive computer software, and intensive, individual tutoring sessions. Important considerations for the design of quality intervention programs were outlined, including the use of careful diagnostic assessments that take into account the child's needs, strengths, weaknesses, and academic and personal history. Research indicated that interventions providing high-quality instruction, and that are based on neurocognitive research allowed for the most effective remediation of dyscalculia, but that adaptive software to train numerical skills could also be a valuable instructional support. FMRI also provided inspiring data suggesting that dyscalculic children's neural processing may be more flexible than was previously believed, and that, with proper intervention, the circuitry of dyscalculic children's brains may be normalized (at least partially), and children's numerical difficulties could be remediated.

One area that requires more investigation involves research on interventions for the remediation of dyscalculia. Are there other games that have been invented? Different instructional methods could also be investigated to determine what neuroscientific changes might result - for example, activities with manipulatives could be compared to activities involving reflective discussions or repetition. Longitudinal studies are also needed to determine the effectiveness of interventions over time, and whether acquired knowledge is transferable to new situations. In addition, definitions, criteria and characteristics of dyscalculia must be formalized – this is an area that requires intensive study and cooperation. In addition, Kucian and von Aster (2015) suggested that experiments be carried out to investigate the grouping of children according to their homogeneous learning profiles rather than in “homogeneous” dyscalculic groups. This would be an excellent area for further research as it might shed some light on the debate over the heterogeneity of dyscalculia.

During the process of writing this paper, I had other questions as well. I found it strange that even though there is a general consensus within the research community regarding dyscalculia’s prevalence, there is still a such significant difference in opinion as to whether dyscalculia is only related to numerical processing, or if other cognitive domains are involved. Why is it that after so many years of behavioral research on dyscalculia, scientists have not been able to determine a clear definition of dyscalculia based on the statistical learning profiles of individuals with dyscalculia? Is this just due to a general lack of cooperation? Why does research on dyscalculia lag behind research on dyslexia to such a large degree? And why is it that when one looks at statistics on world literacy, the statistics always refer to reading literacy, and never to mathematical literacy? Is it because so many people find mathematics difficult, so poor numeracy is considered normal? How does this relate to how we teach mathematics to children? Is it because there is such a large focus in mathematics instruction on abstract symbols and procedures, rather than on the *meaning* of mathematics, and how mathematics is relevant to children’s lives?

Questions like these are extremely relevant to mathematics education and could be examined using critical discourse analysis. These questions are also particularly relevant to dyscalculia, because mathematics is too often taught abstractly, with a focus on procedures. Since research shows that children with dyscalculia struggle with arithmetic procedures and in connecting numerical symbols with their representative quantities, this is poor pedagogical practice.

As a mathematics educator, I plan to use the knowledge that I have gained through the process of writing this thesis to improve my teaching and mathematics instruction in my school. It is considered good teaching practice to anchor instruction to the child’s world, and to make learning real. Considering this, it is imperative that we focus on teaching fundamental mathematical concepts and understanding, and real-life applications of mathematics to all children – particularly ones with dyscalculia that struggle with the meaningfulness of number.

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8 Abbreviations

ADH	Access Deficit Hypothesis
ADHD	Attention Deficit Hyperactivity Disorder
ANS	Approximate Number System
cDD	Dyscalculia with Comorbid Conditions
CT	Computed Tomography
DD	Developmental Dyscalculia
DMN	Default Mode Network
DTI	Diffusion Tensor Imaging
fMRI	Functional Magnetic Resonance Imaging
IPS	Intraparetial Suculus
LFPC	Lateral Fronto-Parietal Cortex
l.AG	left Angular Gyrus
l.CG	left Cingulate Gyrus
l.FG	left Fusiform Gyrus
l.IFL	left Inferior Frontal Lobe
l.IPS	left Intraparietal Sulcus
l.MFPG	left Middle Frontopolar Gyrus
MLD	Mathematical Learning Disability
MRI	Magnetic Resonance Imaging
NCH	Numerosity Coding Hypothesis
OVBM	Optimized Voxel-Based Morphometry
pDD	pure Developmental Dyscalculia
PET	Positron Emission Tomography
PFC	Prefrontal Cortex
r.IPS	right Intraparietal Sulcus
r.MFG	right Middle Frontal Gyrus
SMG	Supramarginal Gyrus
sMRI	Structural Magnetic Resonance Imaging

SPL	Superior Parietal Lobule
VM	Working Memory
VSWM	Visuo-Spatial Working Memory

9 Appendix A

Figure 2 Data table from Kucian et al. (2006)

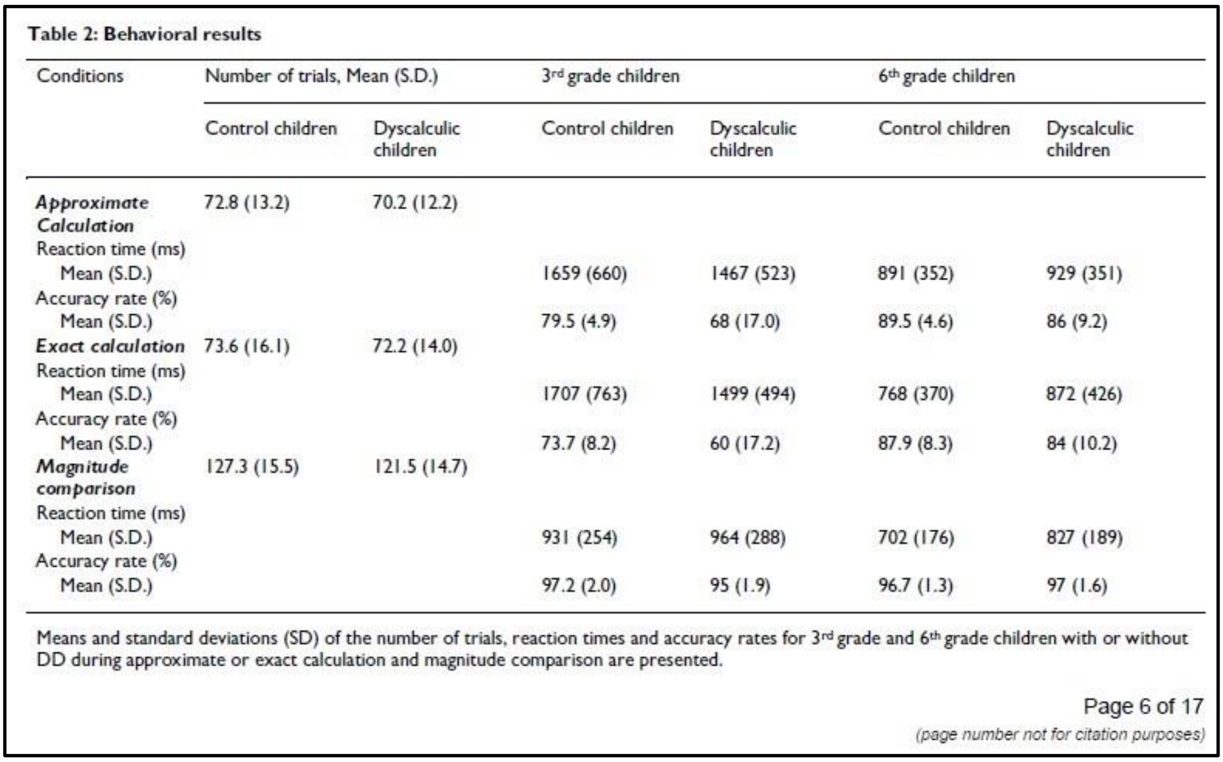

Table 2: Behavioral results

Conditions	Number of trials, Mean (S.D.)		3rd grade children		6th grade children	
	Control children	Dyscalculic children	Control children	Dyscalculic children	Control children	Dyscalculic children
Approximate Calculation	72.8 (13.2)	70.2 (12.2)				
Reaction time (ms)						
Mean (S.D.)			1659 (660)	1467 (523)	891 (352)	929 (351)
Accuracy rate (%)						
Mean (S.D.)			79.5 (4.9)	68 (17.0)	89.5 (4.6)	86 (9.2)
Exact calculation	73.6 (16.1)	72.2 (14.0)				
Reaction time (ms)						
Mean (S.D.)			1707 (763)	1499 (494)	768 (370)	872 (426)
Accuracy rate (%)						
Mean (S.D.)			73.7 (8.2)	60 (17.2)	87.9 (8.3)	84 (10.2)
Magnitude comparison	127.3 (15.5)	121.5 (14.7)				
Reaction time (ms)						
Mean (S.D.)			931 (254)	964 (288)	702 (176)	827 (189)
Accuracy rate (%)						
Mean (S.D.)			97.2 (2.0)	95 (1.9)	96.7 (1.3)	97 (1.6)

Means and standard deviations (SD) of the number of trials, reaction times and accuracy rates for 3rd grade and 6th grade children with or without DD during approximate or exact calculation and magnitude comparison are presented.

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(page number not for citation purposes)

10. Appendix B. Data tables from database searches

Table B1, Database search, WoK, 14.10.2015. Result: 110 hits, including 2 duplicates.

Publ. Date	Author	Title	Incl/Excl, Q-Rating	Journal
2015 08	De Visscher	The interference effect in arithmetic fact solving: An fMRI study	N, Q1	Neuroimage
2015 05	Rubinstein	Link between cognitive neuroscience and education: the case of clinical assessment of developmental dyscalculia	Y, PR, Q2	Frontiers In Human Neuroscience
2015 05	Attout	Working Memory for Serial Order Is Dysfunctional in Adults With a History of Developmental Dyscalculia: Evidence From Behavioral and Neuroimaging Data	U, PR, Q2	Developmental Neuropsychology
2015 05	Rosenberg-Lee	Brain hyper-connectivity and operation-specific deficits during arithmetic problem solving in children with developmental dyscalculia	Y, PR, Q1	Developmental Science
2015 03	Van Rinsveld	The relation between language and arithmetic in bilinguals: insights from different stages of language acquisition	N	Frontiers In Psychology
2015 03	Artemenko	Differential influences of unilateral tDCS over the intraparietal cortex on numerical cognition	U, PR, Q2	Frontiers In Human Neuroscience
2015 03	Emerson	Continuity and change in children's longitudinal neural responses to numbers	Y, PR, Q1	Developmental Science
2015 02	Berteletti	How number line estimation skills relate to neural activations in single digit subtraction problems	Y, PR, Q1	Neuroimage
2015	Woods	Parietal dysfunction during number processing in children with fetal alcohol spectrum disorders.	N, PR, Q1	Neuroimage. Clinical
2015 01	Marques	Biparietal variant of Alzheimer's disease: a rare presentation of a common disease	N, IR	Bmj Case Reports

2015 01	Kucian	Developmental dyscalculia	Y, PR, Q2	European Journal Of Pediatrics
2014 09	Kucian	Developmental dyscalculia: a dysconnection syndrome?	Y, PR, Q1	Brain Structure & Function
2014 08	Berteletti	Children with mathematical learning disability fail in recruiting verbal and numerical brain regions when solving simple multiplication problems	Y, PR, Q1	Cortex
2014 02	Karagiannakis	Mathematical learning difficulties subtypes classification	Y, PR, Q2	Frontiers In Human Neuroscience
2014 02	luculano	Preliminary evidence for performance enhancement following parietal lobe stimulation in Developmental Dyscalculia	Y, PR, Q2	Frontiers In Human Neuroscience
2014 05	Klein	Processing of Intentional and Automatic Number Magnitudes in Children Born Prematurely: Evidence From fMRI	N, PR, Q2	Developmental Neuropsychology
2013 12	Dinkel	Diagnosing Developmental Dyscalculia on the Basis of Reliable Single Case FMRI Methods: Promises and Limitations	Y, PR, Q1	Plos One
2013 12	Tallant	Pretense, Mathematics, and Cognitive Neuroscience	N, IR, Q1	British Journal For The Philosophy Of Science
2013 11	Szucs	Developmental dyscalculia is related to visuo-spatial memory and inhibition impairment	Y, PR, Q1	Cortex
2013 11	Ashkenazi	Neurobiological Underpinnings of Math and Reading Learning Disabilities	U, PR, Q1	Journal Of Learning Disabilities
2013 11	Pinel	Genetic and environmental contributions to brain activation during calculation	N, NR, PR, Q1	Neuroimage
2013 09	Ashkenazi	Visuo-spatial working memory is an important source of domain-general vulnerability in the development of arithmetic cognition	U, PR, Q1	Neuropsychologia
2013 06	Hauser	Enhancing performance in numerical magnitude processing and mental arithmetic using transcranial Direct Current Stimulation (tDCS)	U, PR, Q2	Frontiers In Human Neuroscience
2013 06	Snowball	Long-Term Enhancement of Brain Function and Cognition Using Cognitive Training and Brain Stimulation	U, PR, Q1	Current Biology

2015 04	Lubin	Numerical transcoding proficiency in 10-year-old schoolchildren is associated with gray matter inter-individual differences: a voxel-based rnorphonnetry study	Y, PR, Q1	Frontiers In Psychology
2013 04	Butterworth	Understanding Neurocognitive Developmental Disorders Can Improve Education for All	U, PR, Q1	Science
2013 02	Vuokko	Cortical activation patterns during subitizing and counting	U, PR, Q2	Brain Research
2013 01	Price	Why Mental Arithmetic Counts: Brain Activation during Single Digit Arithmetic Predicts High School Math Scores	Y, PR, Q1	Journal Of Neuroscience
2013 09	Du	Abacus Training Modulates the Neural Correlates of Exact and Approximate Calculations in Chinese Children: An fMRI Study	U, PR, Q3	Biomed Research International
2013 01	Cantlon	Neural Activity during Natural Viewing of Sesame Street Statistically Predicts Test Scores in Early Childhood	U, PR, Q1	Plos Biology
2012 11	Furman	Symbolic and non-symbolic numerical representation in adults with and without developmental dyscalculia	U, PR, Q3	Behavioral And Brain Functions
2012 10	Bugden	The role of the left intraparietal sulcus in the relationship between symbolic number processing and children's arithmetic competence	N, PR? unkn, Q2	Developmental Cognitive Neuroscience
2012 08	Ansari	Neuroeducation - A Critical Overview of An Emerging Field	Y, PR, Q2	Neuroethics
2012 08	Knight	The Emerging Neuroscience of Financial Capacity	N, Pr, Q4	Generations-Journal Of The American Society On Aging
2012 05	Dumontheil	Brain Activity during a Visuospatial Working Memory Task Predicts Arithmetical Performance 2 Years Later	U, PR, Q1	Cerebral Cortex
2012 03	Morocz	Time-resolved and spatio-temporal analysis of complex cognitive processes and their role in disorders like developmental dyscalculia	N, NR, Q3	International Journal Of Imaging Systems And Technology
2012 03	Zhang	Neural correlates of numbers and mathematical terms	U, PR, Q1	Neuroimage

2012 02	Ashkenazi	Weak task-related modulation and stimulus representations during arithmetic problem solving in children with developmental dyscalculia	Y, PR, Q2	Developmental Cognitive Neuroscience
2012 02	Kadosh	Automatic and intentional number processing both rely on intact right parietal cortex: a combined fMRI and neuronavigated TMS study	U, PR, Q2	Frontiers In Human Neuroscience
2012 10	Vicario	Temporal Abnormalities in Children With Developmental Dyscalculia	Y PR, Q2	Developmental Neuropsychology
2011 12	Ansari	Individual differences in mathematical competence modulate brain responses to arithmetic errors: An fMRI study	U?, PR, Q2	Learning And Individual Differences
2011 12	Gullick	Individual differences in working memory, nonverbal IQ and mathematics achievement and brain mechanisms associated with symbolic and nonsymbolic number processing	U, PR, Q2	Learning And Individual Differences
2011 11	Grabner	Brain correlates of mathematical competence in processing mathematical representations	U, PR, Q2	Frontiers In Human Neuroscience
2011 09	Silva	HIV-associated dementia in older adults: clinical and tomographic aspects	N, PR, Q3	International Psychogeriatrics
2011 08	De Smedt	Effects of problem size and arithmetic operation on brain activation during calculation in children with varying levels of arithmetical fluency	Y, PR, Q1	Neuroimage
2011 08	Kucian	Mental number line training in children with developmental dyscalculia	Y, PR, Q1	Neuroimage
2011 08	Goswami	Educational neuroscience: Developmental mechanisms: Towards a conceptual framework	U, PR, Q1	Neuroimage
2011 07	Janoos	Spatio-temporal models of mental processes from fMRI	U, PR, Q1	Neuroimage
2011 06	Marin	Function follows form: understanding brain function from a genetic perspective	N, PR, Q1	Current Opinion In Genetics & Development
2011 05	Butterworth	Dyscalculia: From Brain to Education	Y, PR, Q1	Science
2011 08	Ansari	Introduction to the Special Issue: Toward a Developmental Cognitive Neuroscience of Numerical and Mathematical Cognition	Y, PR, Q2	Developmental Neuropsychology

2011 06	Kucian	Non-Symbolic Numerical Distance Effect in Children With and Without Developmental Dyscalculia: A Parametric fMRI Study	Y, PR, Q2,	Developmental Neuropsychology
2011 06	Kaufmann	Meta-Analyses of Developmental fMRI Studies Investigating Typical and Atypical Trajectories of Number Processing and Calculation	Y, PR, Q2	Developmental Neuropsychology
2011 04	Kesler	Changes in frontal-parietal activation and math skills performance following adaptive number sense training: Preliminary results from a pilot study	N, PR, Q2	Neuropsychological Rehabilitation
2011 07	Oliver	Towards an understanding of neuroscience for science educators	U, PR, Q1	Studies In Science Education
2010 11	Uddin	Dissociable Connectivity within Human Angular Gyrus and Intraparietal Sulcus: Evidence from Functional and Structural Connectivity	U, PR, Q1	Cerebral Cortex
2010 11	Holloway	Developmental Specialization in the Right Intraparietal Sulcus for the Abstract Representation of Numerical Magnitude	U, PR, Q1	Journal Of Cognitive Neuroscience
2010 09	Szucs	An event-related brain potential study of arithmetic syntax	U, PR, Q1	International Journal Of Psychophysiology
2010 08	Meintjes	An fMRI Study of Number Processing in Children With Fetal Alcohol Syndrome	N, PR, Q2	Alcoholism-Clinical And Experimental Research
2010 05	Mussolin	Neural Correlates of Symbolic Number Comparison in Developmental Dyscalculia	Y, PR, Q1	Journal Of Cognitive Neuroscience
2010 04	Geary	Mathematical disabilities: Reflections on cognitive, neuropsychological, and genetic components	Y, PR, Q2	Learning And Individual Differences
2010 02	Cappelletti	The Role of Right and Left Parietal Lobes in the Conceptual Processing of Numbers	U, PR, Q1	Journal Of Cognitive Neuroscience
2010 01	Ashkenazi	Attentional networks in developmental dyscalculia	U, PR, Q3	Behavioral and Brain Functions
2010 01	De Smedt	Cognitive neuroscience meets mathematics education	Y, PR, Q1	Educational Research Review
2009 11	Rotzer	Dysfunctional neural network of spatial working memory contributes to developmental dyscalculia	U, PR, Q2	Neuropsychologia

2009 10	Rubinstein	Co-occurrence of developmental disorders: The case of Developmental Dyscalculia	U, PR, Q2	Cognitive Development
2009 10	Kaufmann	Numerical and non-numerical ordinality processing in children with and without developmental dyscalculia: Evidence from fMRI	Y, PR, Q1	Cognitive Development
2009 10	Davis	Aberrant functional activation in school age children at-risk for mathematical disability: A functional imaging study of simple arithmetic skill	U, PR, Q2	Neuropsychologia
2009 08	Kaufmann	Developmental dyscalculia: compensatory mechanisms in left intraparietal regions in response to nonsymbolic magnitudes	Y, PR, Q3	Behavioral and Brain Functions
2009 06	Cappelletti	Quantity without numbers and numbers without quantity in the parietal cortex	U, PR, Q1	Neuroimage
2009 06	Zamarian	Neuroscience of learning arithmetic-Evidence from brain imaging studies	U, PR, Q1	Neuroscience and Biobehavioral Reviews
2009 02	Ischebeck	Flexible transfer of knowledge in mental arithmetic - An fMRI study	U, PR, Q1	Neuroimage
2009 01	Murphy	A Review Of Mathematical Learning Disabilities In Children With Fragile X Syndrome	N, PR, Q3	Developmental Disabilities Research Reviews
2008 09	Simos	Aberrant spatiotemporal activation profiles associated with math difficulties in children: A magnetic source imaging study	U, PR, Q2	Neuropsychology
2008 09	Krueger	Integral calculus problem solving: an fMRI investigation	N, PR, Q4	Neuroreport
2008 06	Varma	How should educational neuroscience conceptualise the relation between cognition and brain function? Mathematical reasoning as a network process	N, PR, Q4	Educational Research
2008 06	Kaufmann	Dyscalculia: neuroscience and education	Y, PR, Q4	Educational Research
2008 04	Rohrer	Parietal lobe deficits in frontotemporal lobar degeneration caused by a mutation in the progranulin gene	N, PR, Q1	Archives Of Neurology
2008 04	Ashkenazi	Basic numerical processing in left intraparietal sulcus (IPS) acalculia	N, PR, Q1	Cortex

2008 04	Varma	Scientific and Pragmatic Challenges for Bridging Education and Neuroscience	N, PR, Q1	Educational Researcher
2008 01	Murphy	Mathematics Learning Disabilities in Girls With Fragile X or Turner Syndrome During Late Elementary School	N, PR, Q1	Journal Of Learning Disabilities
2008 08	Simon	Overlapping numerical cognition impairments in children with chromosome 22q11.2 deletion or Turner syndromes	N, PR, Q2	Neuropsychologia
2007 12	Price	Impaired parietal magnitude processing in developmental dyscalculia	Y, PR, Q1	Current Biology
2007 11	von Aster	Number development and developmental dyscalculia	Y, PR, Q2	Developmental Medicine And Child Neurology
2007 07	Ischebeck	Imaging early practice effects in arithmetic	U, PR, Q1	Neuroimage
2007 04	Kadosh	Virtual dyscalculia induced by parietal-lobe TMS impairs automatic magnitude processing	Y, PR, Q1	Current Biology : Cb
2006 12	Chen	Prospective demonstration of brain plasticity after intensive abacus-based mental calculation training: An fMRI study	N, PR, Q2/3	Nuclear Instruments & Methods In Physics Research Section A
2006 11	Rubinstein	Double dissociation of functions in developmental dyslexia and dyscalculia	N, PR; Q1	Journal of Educational Psychology
2006 06	Kesler	Neurofunctional differences associated with arithmetic processing in turner syndrome	N, PR, Q1	Cerebral Cortex
2006 05	Kovas	Generalist genes: implications for the cognitive sciences	N, PR, Q1	Trends In Cognitive Science
2006 09	Kucian	Impaired neural networks for approximate calculation in dyscalculic children: a functional MRI study.	Y, PR, Q3	Behavioral And Brain Functions
2006 10	Delazer	Isolated numerical skills in posterior cortical atrophy - An fMRI study	N, PR, Q2	Neuropsychologia
2005 03	Xie	Patterns of brain activation in patients with mild Alzheimer's disease during performance of subtraction - An fMRI study	N, Pr, Q4	Clinical Imaging

2005 03	Varley	Agrammatic but numerate	N, PR,Q1	Proceedings Of The National Academy Of Sciences Of The United States Of America
2005 05	Venkatraman	Neural correlates of symbolic and non-symbolic arithmetic	N, PR, Q2	Neuropsychologia
2004 09	Haskell	A logico-mathematic, structural methodology: Part III, theoretical, evidential, and corroborative bases of a new cognitive unconscious for sub-literal (SubLit) cognition and language	N, PR, Q4	Journal Of Mind And Behavior
2004 07	Schmithorst	Empirical validation of the triple-code model of numerical processing for complex math operations using functional MRI and group Independent Component Analysis of the mental addition and subtraction of fractions	N, PR, Q1	Neuroimage
2004 06	Piazza	From Number Neurons to Mental Arithmetic: The Cognitive Neuroscience of Number Sense	N	Cognitive Neurosciences Iii
2003 11	Molko	Functional and structural alterations of the intraparietal sulcus in a developmental dyscalculia of genetic origin	N, PR, Q1	Neuron
2003 05	Dehaene	Three parietal circuits for number processing	N, PR, Q2	Cognitive Neuropsychology
2002 12	Temple	The developmental cognitive neuroscience approach to the study of developmental disorders	N, PR, Q1	Behavioral and Brain Sciences
2002 11	van Harskamp	Are multiplication facts implemented by the left supramarginal and angular gyri?	N, PR, Q2	Neuropsychologia
2001 04	Gruber	Dissociating neural correlates of cognitive components in mental calculation	N, PR, Q1	Cerebral Cortex
2000 11	Stanescu-Cosson	Understanding dissociations in dyscalculia - A brain imaging study of the impact of number size on the cerebral networks for exact and approximate calculation	N, PR, Q1	Brain
2000 08	Kazui	Cortical activation during retrieval of arithmetical facts and actual calculation: A functional magnetic resonance imaging study	N, PR, Q1	Psychiatry and Clinical Neurosciences

2000 03	Rickard	The calculating brain: an fMRI study	N, PR, Q2	Neuropsychologia
1998 08	Dehaene	Abstract representations of numbers in the animal and human brain	N, PR, Q1	Trends In Neurosciences
1996 01	Levin	Dyscalculia and dyslexia after right hemisphere injury in infancy	N, PR, Q1	Archives of Neurology
2015 08	Evans	Brain Structural Integrity and Intrinsic Functional Connectivity Forecast 6 Year Longitudinal Growth in Children's Numerical Abilities	N, PR, Q1	Journal of Neuroscience

Table B2, Database search, WoK 09.02.2016.

Publ. Date	**Author**	**Title**	**Incl/Excl, Q Rating**	**Journal**
2015 09	Iuculano	Cognitive tutoring induces widespread neuroplasticity and remediates brain function in children with mathematical learning disabilities	Y, PR Q1	Nature Communications
2016 01	Price	The relation between 1st grade grey matter volume and 2nd grade math competence	N, PR Q1	Neuroimage
2016 01	Grotheer	Neuroimaging Evidence of a Bilateral Representation for Visually Presented Number	N, PR Q1	Journal of Neuroscience

Table B3, Database search, PN, 14.12.2015. Result: 65 hits, including 3 doubles + 2 (German/French), 24 non-duplicates.

Publ. Date	Author	Title	Incl/Excl, Q Rating	Journal
2015 10	Jastrzebski	Mathematical impairment associated with high-contrast abnormalities in change detection and magnocellular visual evoked response.	N PR	Experimental Brain Research
2015 08	Huber	A general number-to-space mapping deficit in developmental dyscalculia.	N PR	Research in Developmental Disabilities
2015 05	Davis	Cross-hemispheric collaboration and segregation associated with task difficulty as revealed by structural and functional connectivity.	N PR	The Journal of Neuroscience
2015 01	Clerc	Atypical association of semantic dementia, corticobasal syndrome, and 4R tauopathy	N PR	Neurocase
2014 06	Orraca-Castillo	Neurocognitive profiles of learning disabled children with neurofibromatosis type 1.	N PR	Front Hum Neurosci.
2014 05	Cappelletti	Commonalities for numerical and continuous quantity skills at temporo-parietal junction	N PR	Journal of Cognitive Neuroscience
2014 04	Gnanapavan	A rare presentation of atypical demyelination: Tumefactive multiple sclerosis causing Gerstmann's syndrome	N PR	BMC Neurology
2014 02	Roessler	Improved resection in lesional temporal lobe epilepsy surgery using neuronavigation and intraoperative MR imaging: Favourable long term surgical and seizure outcome in 88 consecutive cases	N PR	Seizure
2013 09	Daniel	Award: Transforming education through neuroscience	N PR	Mind, Brain, and Education
2013 08	Kaufmann	Dyscalculia from a developmental and differential perspective	Y PR	Frontiers in Psychology
2013 07	Cangöz	Computer based screening dyscalculia: Cognitive and neuropsychological correlates	Y PR	The Turkish Online Journal of Educational Technology

2013 01	De Visscher	A case study of arithmetic facts dyscalculia caused by a hypersensitivity-to-interference in memory	N PR	Cortex: A Journal Devoted to the Study of the Nervous System and Behavior
2013 05	Park	Parietal variant Alzheimer's disease presenting with dyscalculia	N PR	Neurological Sciences
2013 04	de Souza	Primary progressive apraxia: A syndrome difficult to categorize	N PR	Arquivos de Neuro-Psiquiatria
2012 01	Estévez	Basic numerical capacities and prevalence of developmental dyscalculia: The Havana Survey.	Y PR Q?	Dev Psychol
2011 12	Noël	Developmental changes in the profiles of dyscalculia: An explanation based on a double exact-and-approximate number representation mode	Y PR Q2	Frontiers in Human Neuroscience
2010 04	Cirino	Introduction: Perspectives on math difficulty and disability in children	Y PR	Learning and Individual Differences
2009 02	Rubinsten	Developmental dyscalculia: Heterogeneity might not mean different mechanisms	Y PR Q1	Trends in Cognitive Sciences
2008 09	Iuculano	Core information processing deficits in developmental dyscalculia and low numeracy	Y PR	Developmental Science
2005 01	Butterworth	The development of arithmetical abilities	Y PR	Journal of Child Psychology and Psychiatry
2004 09	Landerl	Developmental dyscalculia and basic numerical capacities: A study of 8-9-year-old students	Y PR	Cognition
2000 06	Deloche	Cognitive neuropsychological models of adult calculation and number processing: The role of the surface format of numbers	N PR	European Child & Adolescent Psychiatry
1998 01	Kareken	Functional brain imaging in apraxia	N PR	Archives of Neurology
1989 03	Grafman	The progressive breakdown of number processing and calculation ability: A case study	N PR	Cortex

Table B4, Database search, PM, 3.12.2015. Result: 112 hits, 76 non-duplicates.

Publ. Date	**Author**	**Title**	**Incl/Excl, Q Rating**	**Journal**
2015 08	Nakayama	Analysis of risk factors for poor prognosis in conservatively managed early-stage spontaneous osteonecrosis of the knee.	N	Elsevier
2015 08	Sha	Early-onset Alzheimer's disease versus frontotemporal dementia: resolution with genetic diagnoses?	N	Neurocase
2015 09	Klabunde	Examining the neural correlates of emergent equivalence relations in fragile X syndrome.	N	Psychiatry Res
2015 04	Woods	Parietal dysfunction during number processing in children with fetal alcohol spectrum disorders.	N	Neuroimage Clin
2015 08	Huber	A general number-to-space mapping deficit in developmental dyscalculia	N	Res Dev Disabil
2015 05	Rubinsten	Link between cognitive neuroscience and education: the case of clinical assessment of developmental dyscalculia	U	Front Hum Neurosci.
2015 01	Marques IB	Biparietal variant of Alzheimer's disease: a rare presentation of a common disease.	N	BMJ Case Rep.
2014 10	Huber	Dysregulation of the IL-23/IL-17 axis and myeloid factors in secondary progressive MS.	N	Neurology
2014 11	Okamoto N	KIF1A mutation in a patient with progressive neurodegeneration.	N	J Hum Genet
2014 06	Demir	The differential role of verbal and spatial working memory in the neural basis of arithmetic.	N	Dev Neuropsychol
2014 11	Evans	The functional anatomy of single-digit arithmetic in children with developmental dyslexia.	N	Neuroimage

2014 06	Zhang	Building Knowledge Structures by Testing Helps Children With Mathematical Learning Difficulty.	U, Q?	Journal of Learning Disabilities
2014 04	Bhattacharyya	Dyscalculia, dysgraphia, and left-right confusion from a left posterior peri-insular infarct.	N	Behav Neurol.
2014 03	Roessler	Improved resection in lesional temporal lobe epilepsy surgery using neuronavigation and intraoperative MR imaging: favourable long term surgical and seizure outcome in 88 consecutive cases.	N	Seizure
2014 01	Stefansson	CNVs conferring risk of autism or schizophrenia affect cognition in controls.	N	Nature
2013 10	Cappelletti M	Residual number processing in dyscalculia.	N	Neuroimage Clin
2014 01	Pantazatos	Reduced anterior temporal and hippocampal functional connectivity during face processing discriminates individuals with social anxiety disorder from healthy controls and panic disorder, and increases following treatment.	N	Neuropsychopharmacology
2013 06	Ripellino P	Clinical presentation of left angular gyrus ischaemic lesion: finger agnosia, acalculia, agraphia, left-right disorientation and episodic autoscopia.	N	BMJ Case Rep.
2013 02	Ludwig	A common variant in myosin-18B contributes to mathematical abilities in children with dyslexia and intraparietal sulcus variability in adults.	N	Transl Psychiatry
2014 04	Asada	Effects of mental rotation on acalculia: differences in the direction of mental rotation account for the differing characteristics of acalculia induced by right and left hemispheric brain injury.	N	Neurocase
2013 05	Cerasa A	MR imaging and cognitive correlates of relapsing-remitting multiple sclerosis patients with cerebellar symptoms.	N	J Neurol
2012 09	Courtois	Lymphomatosis cerebri Presenting as a Recurrent Leukoencephalopathy.	N	Case Rep Neurol.
2012 05	Soares-Ishigaki	Aphasia and herpes virus encephalitis: a case study.	N	Sao Paulo Med J

2012 11	Elliott	Magnetic resonance imaging changes in the size and shape of the oropharynx following acute whiplash injury.	N	J Orthop Sports Phys Ther
2012 06	Sherman	Detecting epilepsy-related cognitive problems in clinically referred children with epilepsy: is the WISC-IV a useful tool?	N	Epilepsia
2011 12	Cappelletti	Time processing in dyscalculia.	N	Front Psychol
2011 06	Rubinsten	Processing ordinality and quantity: the case of developmental dyscalculia.	N	PLoS One
2012 01	Reigosa-Crespo	Basic numerical capacities and prevalence of developmental dyscalculia: the Havana Survey.	Y, PR Q?	Dev Psychol
2011 12	Kleinschmidt	Gerstmann meets Geschwind: a crossing (or kissing) variant of a subcortical disconnection syndrome?	N	Neuroscientist
2011 09	Brito e Silva	HIV-associated dementia in older adults: clinical and tomographic aspects.	N	Int Psychogeriatr
2011 08	Quattrocchi	Modic changes: anatomy, pathophysiology and clinical correlation.	N	Acta Neurochir Suppl
2010 12	Butterworth	Foundational numerical capacities and the origins of dyscalculia.	Y PR Q1	TRENDS IN COGNITIVE SCIENCE
2010 10	Calabrese	Imaging distribution and frequency of cortical lesions in patients with multiple sclerosis.	N	Neurology
2010 07	Rubinsten	Mathematics anxiety in children with developmental dyscalculia.	N	Behav Brain Funct
2010 08	Chanraud	Dual tasking and working memory in alcoholism: relation to frontocerebellar circuitry.	N	Neuropsychopharmacology
2010 08	Trivedi	Correlation of quantitative sensorimotor tractography with clinical grade of cerebral palsy.	N	Neuroradiology
2010 02	Lünemann	Elevated Epstein-Barr virus-encoded nuclear antigen-1 immune responses predict conversion to multiple sclerosis.	N	Ann Neurol

2010 02	Giorgio	Relationships of brain white matter microstructure with clinical and MR measures in relapsing-remitting multiple sclerosis.	N	J Magn Reson Imaging
2010 11	Kodituwakku	A neurodevelopmental framework for the development of interventions for children with fetal alcohol spectrum disorders.	N	Alcohol
2010 04	Patanella	Correlations between peripheral blood mononuclear cell production of BDNF, TNF-alpha, IL-6, IL-10 and cognitive performances in multiple sclerosis patients.	N	J Neurosci Res
2009 08	Ota	Visualization of calculation centres by functional MRI for neurosurgery.	N	Br J Neurosurg
2009 02	Krajbich	Economic games quantify diminished sense of guilt in patients with damage to the prefrontal cortex.	N	J Neurosci
2008 01	Moro	Finger recognition and gesture imitation in Gerstmann's syndrome.	N	Neurocase
2008 07	Kezele	Atrophy in white matter fiber tracts in multiple sclerosis is not dependent on tract length or local white matter lesions.	N	Multip Scler
2008 04	Perkins	Benign rolandic epilepsy -- perhaps not so benign: use of magnetic source imaging as a predictor of outcome.	N	J Child Neurol
2007 11	Kadosh	Dyscalculia.	N	Curr Biol
2008 02	Reich	Corticospinal tract abnormalities are associated with weakness in multiple sclerosis.	N	AJNR Am J Neuroradiol
2008 01	Rotzer	Optimized voxel-based morphometry in children with developmental dyscalculia.	Y, PR, Q1	Neuroimage
2007 09	Braga	Magnetic resonance imaging (MRI) findings and neuropsychological sequelae in children after severe traumatic brain injury: the role of cerebellar lesion.	N	J Child Neurol
2007 09	Raznahan	Biological markers of intellectual disability in tuberous sclerosis.	N	Psychol Med
2006 10	McDonald	Musical alexia with recovery: a personal account.	N	Brain

2006 09	MacKenzie-Graham	Cerebellar cortical atrophy in experimental autoimmune encephalomyelitis.	N	Neuroimage
2006 12	Gross-Tsur	Evidence of a developmental cerebello-cerebral disorder.	N	Neuropsychologia
2006 06	Dowker	What can functional brain imaging studies tell us about typical and atypical cognitive development in children?	U, Ch/Ad	J Physiol Paris
2005 10	Spencer	Qualitative assessment of brain anomalies in adolescents with mental retardation.	N	AJNR Am J Neuroradiol.
2005 04	Nagata	Lateral transsulcal approach to asymptomatic trigonal meningiomas with correlative microsurgical anatomy: technical case report.	N	Neurosurgery
2005 03	Casseron	DOPA-sensitive dystonia-plus syndrome.	N	Dev Med Child Neurol
2005 03	Simon	Volumetric, connective, and morphologic changes in the brains of children with chromosome 22q11.2 deletion syndrome: an integrative study.	N	Neuroimage
2004 10	Patil	Glutaric aciduria type I associated with learning disability.	N	Indian J Pediatr
2004 08	Butterbaugh	Lateralization of temporal lobe epilepsy and learning disabilities, as defined by disability-related civil rights law.	N	Epilepsia
2008 08	Roman	Neuropsychological deficits in a child with a left penetrating brain injury.	N	Brain Inj
2002 09	Zorzon	Depressive symptoms and MRI changes in multiple sclerosis.	N	Eur J Neurol
2001 03	Hanoglu	Cognitive dysfunction of right hemisphere-like Todd's paralysis after status epilepticus: a case report.	N	Seizure
2000 09	Bzufka	Neuropsychological differentiation of subnormal arithmetic abilities in children.	U, Ad?	European Child & Adolescent Psychiatry
2000 09	Neumärker	Mathematics and the brain: uncharted territory?	U, Ad?	European Child & Adolescent Psychiatry

2000 10	Cohen	Language and calculation within the parietal lobe: a combined cognitive, anatomical and fMRI study.	N	Neuropsychologia
2000 04	Suresh	Developmental Gerstmann's syndrome: a distinct clinical entity of learning disabilities.	N	Pediatr Neurol
1999 06	Mayer	A pure case of Gerstmann syndrome with a subangular lesion.	N	Brain
1999 01	Oki	Cognitive deterioration associated with focal cortical dysplasia.	N	Pediatr Neurol
1995 02	Kennedy	Chromosome 14 linked familial Alzheimer's disease. A clinico-pathological study of a single pedigree.	N	Brain
1993 09	Rossor	Alzheimer's disease families with amyloid precursor protein mutations.	N	Ann N Y Acad Sci
1993 03	Lucchelli	Primary dyscalculia after a medial frontal lesion of the left hemisphere.	N	J Neurol Neurosurg Psychiatry
1992 02	Evrard	Watershed cerebral infarcts: retrospective study of 24 cases.	N	Neurol Res
1991 08	Selnes	Limb apraxia without aphasia from a left sided lesion in a right-handed patient.	N	J Neurol Neurosurg Psychiatry
1991 04	Moore	Right parietal stroke with Gerstmann's syndrome. Appearance on computed tomography, magnetic resonance imaging, and single-photon emission computed tomography.	N	Arch Neurol
1990 09	Andoh	Tumors at the trigone of the lateral ventricle--clinical analysis of eight cases.	N	Neurol Med Chir

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Publ. Date	**Author**	**Title**	**Incl/Excl, Q Rating**
2015 10	Garcia-Ramos	Cognition and brain development in children with benign epilepsy with centrotemporal spikes	N