EARLY NUMERICAL COMPETENCIES AND MATHEMATICAL ABILITIES

IN CHILDREN WITH AUTISM SPECTRUM DISORDER

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Early numerical competencies and mathematical abilities in children with autism spectrum disorder

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CONTENTS

CHAPTER 1

GENERAL INTRODUCTION

Recently, the interest in the academic functioning of children with autism spectrum disorder (ASD) has grown because of their increasing inclusion in mainstream educational settings. Although teachers and therapists often consider mathematics as a stumbling block for children with ASD, the amount of literature on this topic does not match this concern. In this chapter, the theoretical background of this doctoral dissertation will be discussed, along with the objectives of the research. Furthermore, an overview of the chapters included in this dissertation will be given.

DEFINING AUTISM SPECTRUM DISORDERS

This doctoral research was conducted at a moment at which the *Diagnostic and Statistical Manual of Mental Disorders, 4th edition, Text Revision* (*DSM-IV-TR*; American Psyciatric Association [APA], 2000) was the prevailing version of the *DSM* classification system. As such, all participating clinical children were diagnosed according to the criteria of the *DSM-IV-TR*, which used the concept of *pervasive developmental disorders* (*PDDs*) as a general heading for Autistic Disorder, Asperger's Disorder (AD), Pervasive Developmental Disorder Not Otherwise Specified (PDD-NOS), Childhood Disintegrative Disorder, and Rett's Disorder. PDDs are characterized by qualitative impairments in reciprocal social interaction and qualitative impairments in verbal and nonverbal communication, accompanied by restrictive, repetitive, and stereotyped patterns of interests, activities, and behaviors (APA, 2000).

Because the validity of the distinction among the different subtypes according to the *DSM-IV-TR* was questionable (e.g., Snow & Lecavalier, 2011; Witwer & Lecavalier, 2008), the term *autism spectrum disorder* made its entrance both in literature and clinical practice. Although the term was sometimes used to refer to all five PDDs, far more often it was used as an umbrella term for the first three subtypes only, because Childhood Disintegrative Disorder and Rett's Disorder show a different developmental course and prognosis (Willemsen-Swinkels & Buitelaar, 2002).

The current version of the *DSM*, *DSM-5* (APA, 2013), has responded to this evolution and diagnostic criteria were altered. *DSM-5* mentions only the single category of autism spectrum disorder, which incorporates the previous subtypes of Autistic Disorder, AD, PDD-NOS, and Childhood Disintegrative Disorder, whereas Rett's Disorder is no longer included (APA, 2013). Moreover, the triad of symptoms has been merged into two domains: Qualitative impairments in social interaction and communication are subsumed into the first domain, whereas the second domain consists of the restricted, repetitive patterns of behavior, interests, or activities (APA, 2013).

In this dissertation, the term autism spectrum disorder (ASD) is used to refer to the broad spectrum of autism, making no distinctions between the different diagnostic subtypes that were previously used. This being the case, it can nevertheless be pointed out that none of the participating children were diagnosed with Childhood Disintegrative

Disorder or Rett's Disorder. Preliminary evidence suggests that most children with *DSM-IV* PDD diagnoses would remain eligible for an ASD diagnosis under the *DSM-5* criteria (Huerta, Bishop, Duncan, Hus, & Lord, 2012; Kent et al., 2013), although some studies indicate that high-functioning individuals (i.e., individuals with AD or PDD-NOS) are less likely to meet *DSM-5* criteria than children with Autistic Disorder (Mayes et al., 2014; Young & Rodi, 2014).

Estimates of the prevalence of ASD vary considerably between studies, with figures ranging from 0.28% to 2.64% (Baird et al., 2006; Chakrabarti & Fombonne, 2005; Kim et al., 2011; Paula, Ribeiro, Fombonne, & Mercadante, 2011). This large variation is due to differences in sample size, population age, strictness of diagnostic criteria, and geographical area of the study (Williams, Higgins, & Brayne, 2006). Moreover, the prevalence of ASD seems to have increased over the last decades, probably reflecting better identification and the use of a broader diagnostic concept (Elsabbagh et al., 2012; Rutter, 2005). Usually, a prevalence rate of 60 to 70 out of 10,000 children is put forward as general estimate, making ASDs one of the more frequent childhood neurodevelopmental disorders (Chakrabarti & Fombonne, 2005; Elsabbagh et al., 2012; Fombonne, 2009). The overall gender ratio has traditionally been reported at 4:1, with a higher number of boys than girls being affected (Fombonne, 2009). However, this ratio depends on the level of intellectual functioning, with more pronounced gender differences in children with average to good cognitive abilities than in children with moderate to severe intellectual disability (Fombonne, 2003).

EARLY NUMERICAL COMPETENCIES AND MATHEMATICAL ABILITIES

The importance of numbers

Numbers are not only important in a school context, but also inherent to many aspects of everyday life: Following a recipe is not possible unless you understand the listed weights or measures; keeping track of your expenses requires you to perform basic arithmetic operations; getting somewhere in time requires you to read the clock; and being able to calculate fractions may come in handy during sales. Mathematics is of central importance to modern society and becomes increasingly essential in many job profiles (Engberg & Wolniak, 2013; N. C. Jordan & Levine, 2009). Research evidence illustrates the influence of numerical abilities on employment, promotion opportunities, and wages, over and above the influence of literacy (Geary, 2011b). Given the high social and individual cost associated with poorly developed mathematical skills (Geary, 2011b), it is essential to gain insight into the processes underlying typical and atypical mathematical development.

Mathematical learning disorders

Children with a specific learning disorder with impairment in mathematics, also called *mathematical learning disorder* (*MLD*), show a significant degree of impairment in mathematics, manifesting itself in difficulties with mastering number sense, number facts, calculation, or mathematical reasoning (APA, 2013). The mathematical abilities of individuals with MLD situate themselves substantially and quantifiably below those expected for the individual's chronological age, causing interference with academic performance (APA, 2013). In addition, the symptoms persist for at least 6 months despite the provision of interventions that target the specific difficulties (APA, 2013). Finally, the MLD-related problems cannot be better accounted for by intellectual disabilities or external factors (such as inadequate educational instruction) that could provide sufficient evidence for scholastic failure (APA, 2013).

MLDs are not uncommon: Based on recent studies, the prevalence of MLD in the general school-aged population varies between 2.27% and 14% depending on the country of the study and the diagnostic criteria used (Barbaresi, Katusic, Colligan, Weaver, & Jacobsen, 2005; Desoete, Roeyers, & De Clercq, 2004; Dowker, 2005; Geary, 2011b; Shalev, Manor, & Gross-Tsur, 2005). Indeed, prevalence studies have used highly variable cut-off criteria leading to a variety of concepts for overlapping phenomena, making comparisons of prevalence estimates a hazardous undertaking (Butterworth, 2005b; Desoete et al., 2004; Mazzocco, 2007; Szűcs & Goswami, 2013). MLDs are not only associated with difficulties during the educational career, but may in some cases also impact negatively upon self-esteem, self-perception, and motivation (Elksnin & Elksnin, 2004; Gadeyne, Ghesquiere, & Onghena, 2004; Grolnick & Ryan, 1990). Moreover, this condition can have its influence on employment and day-to-day activities beyond school age (Geary, 2011b). The awareness of these severe and long-term consequences associated with MLDs has stimulated research on early predictors and risk factors of MLD (Powell & Fuchs, 2012). These studies were driven by the intention to improve early identification and intervention, in order to prevent vulnerable children from falling further behind or to develop mathematical difficulties (Coleman, Buysse, & Neitzel, 2006; Fuchs et al., 2007; Gersten, Jordan, & Flojo, 2005; Pasnak, Cooke, & Hendricks, 2006; Passolunghi & Lanfranchi, 2012).

Early numerical competencies in preschool[1]

Children enter elementary school with varying levels of early number competencies. This variety might be due to child characteristics, such as general cognitive abilities, domain-specific numerical abilities, or executive functions; as well as environmental factors, such as early home experiences or socioeconomic status (N. C. Jordan & Levine, 2009; Kroesbergen, van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; Passolunghi & Lanfranchi, 2012; Powell & Fuchs, 2012). Although it is clear that these early numerical competencies can be differentiated from the more complex mathematical knowledge acquired through formal schooling, there is no consensus on the precise definition or even the term used to describe this set of abilities (Berch, 2005; Gersten et al., 2005; Kroesbergen, van Luit, & Aunio, 2012). This lack of agreement gives rise to an abundance of concepts to define these abilities, such as early numeracy (Kroesbergen et al., 2012), number sense, number knowledge, number competence (N. C. Jordan & Levine, 2009; Locuniak & Jordan, 2008), and early numerical competencies (Powell & Fuchs, 2012). Likewise, many different operationalizations exist for these overlapping concepts, with some studies focusing on counting and Piagetian skills, whereas others put emphasis on more basic numerical skills, such as magnitude comparison (Kroesbergen et al., 2012).

Several studies have lent support for the predictive value of the following early numerical competencies for later mathematics performance in typically developing children and children with MLD: verbal subitizing (e.g., Reigosa-Crespo et al., 2012), counting (e.g., Aunola, Leskinen, Lerkkanen, & Nurmi, 2004), magnitude comparison (e.g., De Smedt, Verschaffel, & Ghesquiere, 2009), estimation (e.g., Siegler & Booth,

[1] The way in which the early numerical competencies in preschool as well as the mathematical abilities in elementary school were operationalized in this dissertation is provided in the Appendix.

2004), and arithmetic operations (e.g., N. C. Jordan, Glutting, & Ramineni, 2010). For each of these early numerical competencies, a short definition and developmental pathway will be provided, followed by a demonstration of its importance for later mathematical functioning.

Verbal subitizing. *Subitizing* is the rapid (40-100 ms/item) and accurate assessment of small quantities of up to three (or four) items (Kaufman, Lord, Reese, & Volkmann, 1949). Subitizing deals with nonsymbolic stimuli (i.e., quantities or magnitudes); the aspect "verbal" refers to the mapping of number words onto these magnitudes. Whereas children use counting to determine the exact numerosity of a large set of items, subitizing is considered to be a more automatic process for the precise representation of small numerosities (Dehaene, 1992; Nan, Knosche, & Luo, 2006). A typical signature of an enumeration task, which is used to assess the verbal subitizing abilities, is the *elbow effect* in the reaction time curve (Dehaene, 1992): Whereas the reaction time curve seems to be almost flat for sets of up to three to four items, the enumeration of larger numerosities shows a much steeper linear increase of 200 to 400 ms per item, resulting in a "breakpoint" at numerosity three or four (Dehaene, 1992). Although many theories used this observation to conceptualize subitizing and counting as two qualitatively different and separable processes of distinct cognitive and neural nature (Kaufman et al., 1949; Mandler & Shebo, 1982; Peterson & Simon, 2000; Trick & Pylyshyn, 1993), this dichotomy became a subject of debate (Balakrishnan & Ashby, 1991, 1992; Piazza, Mechelli, Butterworth, & Price, 2002). As such, some authors proposed that the two processes are not different in nature, but reflect two different levels along a continuum of complexity (Piazza et al., 2002). Up till now, the "subitizing-counting" processes still remain topic of scientific controversy (Schleifer & Landerl, 2011). Although a complete overview of this discussion falls beyond the scope of this dissertation, it can be stated that this subitizing-counting controversy sparked a lot of research of different perspectives on this topic. Several authors tried for example to characterize the developmental nature of subitizing. Trick and Pylyshyn (1994) suggested that increasing familiarity with numbers would lead to flatter slopes in the subitizing range with age. Several studies have indeed reported shallower slopes in the subitizing range for older children than for younger ones (Basak & Verhaeghen, 2003; Trick, Enns, & Brodeur, 1996), an effect that levels off at about 8-10 years of age (Reeve, Reynolds, Humberstone, & Butterworth, 2012; Svenson & Sjoberg, 1983). Regarding the size of the subitizing range, Svenson and Sjoberg (1983) reported a change from three to four items from childhood to adulthood, whereas Reeve et al. (2012) stated that four items could already be subitized from 6 years on.

Various studies demonstrated that subitizing is an important factor in mathematical development (Landerl, Bevan, & Butterworth, 2004; Penner-Wilger et al., 2007; Träff, 2013), and longitudinal research showed that subitizing is a domain-specific predictor for later mathematical performance over and above domain-general abilities (Gray & Reeve, 2014; Krajewski & Schneider, 2009; Kroesbergen et al., 2009; LeFevre et al., 2010; Reigosa-Crespo et al., 2012). Moreover, subitizing is sometimes investigated as a core deficit in children with MLD (Fischer, Gebhardt, & Hartnegg, 2008; Schleifer & Landerl, 2011). As such, it has been demonstrated that children with MLD are slower in subitizing tasks compared to typically achieving children (Koontz & Berch, 1996; Landerl et al., 2004; Schleifer & Landerl, 2011) and often do not show a point of discontinuity in their reaction time curves (Koontz & Berch, 1996; Landerl et al., 2004). However, there is no consensus on this subitizing problem, because some studies did not support children with MLD being slower in the enumeration of small numerosities (De Smedt & Gilmore, 2011; Rousselle & Noël, 2007). Following on from this, some studies indeed revealed that some of the children with MLD – but not all of them – have subitizing problems (Desoete & Grégoire, 2006; Fischer et al., 2008).

Counting. *Counting* has been described as the key ability that forms the bridge between the innate number sense and the more advanced mathematical abilities that are culturally expected (Butterworth, 2005a). Dowker (2005) suggested that counting knowledge is not a unitary concept but can be subdivided into procedural and conceptual aspects. Although closely related to each other, these two aspects seem to be mastered separately (Dowker, 2005). Procedural counting knowledge is defined as children’s ability to perform a mathematical task, for example, when a child can successfully determine that there are five objects in an array (LeFevre et al., 2006). Conceptual counting knowledge can be defined as the understanding of the five counting principles formulated by Gelman and Galistel (1978), with three essential principles (i.e., word-object correspondence, stable order, and cardinality) and two unessential principles (i.e., abstraction and order irrelevance) that do not result in incorrect counting. As such, conceptual counting knowledge reflects a child's understanding of why a procedure works or whether a procedure is legitimate (Bisanz & LeFevre, 1992; Hiebert & Lefevre, 1986; LeFevre et al., 2006). Previous studies indicated that children master the essential counting principles at age 4 to 5, but some children acquire these abilities only later on (Le Corre & Carey, 2007; Stock, Desoete, & Roeyers, 2009). Some authors claim that conceptual knowledge develops before procedural knowledge (Gelman & Galistel, 1978; Gelman, Meck, & Merkin, 1986), others suggest the opposite (Briars & Siegler, 1984; Frye, Braisby, Lowe, Maroudas, & Nicholls, 1989). However, the development of conceptual and procedural knowledge may more likely result from iterative processes, in which both aspects build upon each other (Rittle-Johnson & Siegler, 1998; Rittle-Johnson, Siegler, & Alibali, 2001).

Since the 1980s, a large body of evidence has proven the central influence of counting on the development of adequate mathematical abilities and its supporting role in early mathematical strategies (Aunola et al., 2004; Fuson, 1988; Le Corre, Van de Walle, Brannon, & Carey, 2006; Wynn, 1990). Both aforementioned aspects of counting have been reported to be predictive for later mathematical achievement: Whereas procedural counting knowledge is predictive for numerical facility, conceptual counting knowledge is predictive for untimed mathematical achievement (Desoete, Stock, Schepens, Baeyens, & Roeyers, 2009). Moreover, children with MLD show deficient counting abilities, again indicating the importance of adequate and flexible counting knowledge (Dowker, 2005; Geary, Bowthomas, & Yao, 1992; LeFevre et al., 2006).

Magnitude comparison. *Magnitude comparison* is the ability to discriminate two quantities with the intention to point out the largest of both (Gersten et al., 2012). To do this successfully, individuals rely on the *approximate number system* to determine especially larger numerosities in an approximate manner (Halberda & Feigenson, 2008). Although with smaller numerosities one cannot rule out the possibility that children use qualitatively different processes than approximate estimation (such as for example subitizing) to solve a magnitude comparison task (Lonnemann, Linkersdorfer, Hasselhorn, & Lindberg, 2011), it is not unusual to also include smaller numerosities in this task and to link them to the approximate number system (see for example Fuhs & McNeil, 2013; Mazzocco, Feigenson, & Halberda, 2011b; Mundy & Gilmore, 2009). A well-known behavioral signature of this approximate number system is *Weber's law*, which implies that in order to be able to successfully discriminate two quantities, the distance or ratio between them has to be large enough (Halberda & Feigenson, 2008). For example, subjects are faster and more accurate in discriminating four versus nine dots than four versus seven dots. In its most rudimental form, magnitude comparison can be traced back to number discrimination in infants as young as 6 months old (e.g., Xu & Spelke, 2000). As children grow older, the approximate number system acuity increases over the life span with 3-year-olds being able to successfully discriminate numerosities differing by a 3:4 ratio and 6-year-olds with a 5:6 ratio (Halberda & Feigenson, 2008; Piazza et al., 2010). The smallest ratio at which adults are found to successfully discriminate two quantities is 10:11 (Halberda & Feigenson, 2008).

Although number comparison has proven to play an important role in the development of mathematical abilities (De Smedt et al., 2009; Holloway & Ansari, 2009; N. C. Jordan et al., 2010), there is still debate on whether nonsymbolic number comparison (i.e., magnitude comparison) as well as symbolic number comparison performance relates to later mathematics. Whereas some researchers state it does (Halberda, Mazzocco, & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2013; Mazzocco et al., 2011b), others endorse only the contribution of symbolic number comparison at young age (Bartelet, Vaessen, Blomert, & Ansari, 2014; Holloway & Ansari, 2009; Sasanguie, De Smedt, Defever, & Reynvoet, 2012; Sasanguie, Gobel, Moll, Smets, & Reynvoet, 2013). Furthermore, several studies demonstrated a severe impairment in approximate number system acuity (using both symbolic and nonsymbolic stimuli in a number comparison task) in children with MLD (Landerl et al., 2004; Mazzocco, Feigenson, & Halberda, 2011a; Piazza et al., 2010).

Estimation. *Estimation* is an important process both in classroom and in everyday life. Often, a number line estimation task – in which individuals have to locate the position of a given number on a number line – is used to investigate this ability (Siegler & Opfer, 2003). The gain in precision of number line judgments is characterized by a developmental transition from a logarithmic representation to a linear one, suggesting a changing representation with increasing formal schooling (Siegler & Booth, 2004; Siegler & Opfer, 2003). A logarithmic representation compresses the distance between magnitudes at the middle and upper ends of an interval (Siegler & Booth, 2004), whereas a linear representation provides an adequate reflection of the actual numbers.

The age at which this shift occurs depends upon the numerical context (Berteletti, Lucangeli, Piazza, Dehaene, & Zorzi, 2010): For a 0-1000 interval it is situated at sixth grade (Siegler & Opfer, 2003), whereas for a 0-100 interval it is situated at second grade (Siegler & Booth, 2004), and for a 0-10 interval even at preschool age (± 5 years of age; Berteletti et al., 2010). This implies that multiple representations of the same number coexist and that it depends upon age and experience which representation will be triggered (Berteletti et al., 2010). Until recently, most research on number line estimation focused on the positioning of Arabic numerals – whether or not read out loud – on a number line (e.g., Berteletti et al., 2010; Siegler & Booth, 2004; Siegler & Opfer, 2003). However, interest in the comparison of symbolic and nonsymbolic mathematics performance has stimulated the inclusion of nonsymbolic stimuli in number line estimation tasks (Sasanguie et al., 2013; Sasanguie, Van den Bussche, & Reynvoet, 2012).

Several studies support the importance of number-space mapping for mathematical abilities: The linearity of number line judgments has proven to be positively correlated with math achievement scores (Ashcraft & Moore, 2012; Siegler & Booth, 2004). Moreover, estimation accuracy (measured with mean percentages of error on the number line estimation task) has proven to be a unique predictor of mathematical achievement later on, next to the predictive role of linearity (Sasanguie et al., 2013; Sasanguie, Van den Bussche, & Reynvoet, 2012). Furthermore, children with MLD are less accurate in their judgments and rely more on a logarithmic representation when dealing with this task compared to typically achieving children (e.g., Geary, Hoard, Nugent, & Byrd-Craven, 2008; Landerl, 2013).

Arithmetic operations. *Arithmetic operations* find themselves on the border between early numerical competencies and the more advanced mathematical knowledge acquired through formal schooling (Purpura & Lonigan, 2013). Understanding the composition and decomposition of groups by differentiating sets and subsets is necessary in order to successfully solve these kinds of exercises (Purpura & Lonigan, 2013). A first step to learn these simple addition and subtraction tasks is often the use of manipulatives, followed by finger counting, and eventually the use of reasoning strategies and memory-based retrieval (Groen & Resnick, 1977; Powell & Fuchs, 2012). Arithmetic operations can be measured in many different ways: through simple addition and subtraction exercises, such as story problems either with or without manipulatives (e.g., "I have two red flowers and three yellow ones. How many flowers are there altogether?"; Clements & Sarama, 2007; N. C. Jordan, Kaplan, Olah, & Locuniak, 2006; Klein, Starkey, & Ramirez, 2002); two-set addition (i.e., Objects are added to two separate containers. Children have to determine whether the two containers have the same number of objects. Objects are then added or subtracted from one of the containers and the child is asked the same question again; Klein et al., 2002); (de)composition of sets (i.e., The child is presented with a number of objects. Covering the objects, the examiner adds or subtracts a number of objects. After shown the new total of objects, the child has to identify how many objects were added or subtracted; Clements & Sarama, 2007); and number combinations (e.g., "How much is two plus seven?"; Purpura & Lonigan, 2013). Although formal arithmetic problems (e.g., "2 + 2 = ?") are only presented in elementary school, many preschoolers already have an understanding of the numerical transformations involving addition and subtraction at 5 or 6 years of age (Huttenlocher, Jordan, & Levine, 1994). It should be noted that the ability to solve purely nonverbal calculation exercises emerges one to two years earlier (at around 4 years of age) than a comparable success rate at verbal story problems or number fact problems (Levine, Jordan, & Huttenlocher, 1992). Extending this logic, it seems reasonable to assume that the ability to solve visually supported story problems emerges somewhere in between.

Several studies demonstrated a relationship between arithmetic operations and math achievement (N. C. Jordan et al., 2010; N. C. Jordan, Kaplan, Ramineni, & Locuniak, 2009). Arithmetic operations, as part of a larger early numerical competencies battery, have proven to be predictive for later mathematical abilities, especially for applied problem solving (N. C. Jordan et al., 2010). Moreover, children with MLD perform worse on mathematical story problems than typically achieving peers (Hanich, Jordan, Kaplan, & Dick, 2001; N. C. Jordan & Hanich, 2000).

Up till now, the majority of the studies investigating the predictive value of these early numerical competencies only relates one of these competencies to one outcome score (e.g., Siegler & Booth, 2004) or treats several competencies as one domain-specific component as opposed to a domain-general factor (e.g., Hornung, Schiltz, Brunner, &

Martin, 2014; Passolunghi & Lanfranchi, 2012). However, N. C. Jordan and Levine (2009) combined these five components into one model, considering them as five mathematical building blocks upon which later mathematics is built. This combination provides an easy tool to investigate these five competencies in a more convenient way, including all components simultaneously. As such, this doctoral dissertation is based on this model, with the exception of two small deviations. First, although the authors themselves use the terms *number sense*, *number knowledge*, or *number competence* (N. C. Jordan & Levine, 2009), we preferred the term *early numerical competencies* (Powell & Fuchs, 2012) to describe this set of five abilities. This term was chosen because it was deemed less confusing than number sense (which is sometimes defined as restricted to a biologically based lower order sense of quantity, but sometimes considered as a more general higher order and acquired conceptual understanding of mathematics; Berch, 2005). In addition, it stresses more the abilities as precursors compared to the terms number knowledge or number competence. The second deviation relates to the just mentioned divergent views on number sense. When describing the early mathematics foundation, N. C. Jordan and Levine (2009) make a distinction between preverbal number knowledge (i.e., lower order number sense) and symbolic number knowledge (i.e., higher order number sense). Preverbal number knowledge is considered as an ability that is present before verbal input or instruction and that is restricted to nonsymbolic stimuli (N. C. Jordan & Levine, 2009). This closely resembles the construct of number sense as defined by Dehaene (2001), namely, the ability to quickly understand, approximate, and manipulate numerical quantities. This universal preverbal number knowledge provides the foundation for the symbolic number knowledge that is much more prone to experience and schooling and involves symbolic stimuli (Feigenson, Dehaene, & Spelke, 2004; N. C. Jordan & Levine, 2009). N. C. Jordan and Levine (2009) restrict the five aforementioned early numerical competencies to this second higher order category. However, the two perspectives on number sense are not in contrast with each other. On the contrary, they are closely connected because the foundational lower order preverbal number knowledge is incorporated in children’s symbolic number knowledge (N. C. Jordan et al., 2010). Consider for example the concept of subitizing. Benoit, Lehalle, and Jouen (2004) differentiate between different kinds of subitizing abilities. One of these abilities comprises the perceptual-preverbal ability (i.e., small number discrimination) to recognize and distinguish small numbers (e.g., Tan & Bryant, 2000), an ability that can be categorized under the preverbal number knowledge. Another, more traditional, use of the word subitizing refers to a perceptual-verbal ability (i.e., verbal subitizing), in which verbal naming of the presented numerosity is required (e.g., Klahr & Wallace, 1976). As such, this latter ability can be categorized under the symbolic number knowledge. However, both kinds of subitizing are entangled in the same developmental pathway (Benoit et al., 2004). Given this close connection between preverbal and symbolic number knowledge, we decided to incorporate both symbolic and nonsymbolic tasks as early numerical competencies. As such, our focus lies on the distinction between early numerical competencies as precursors at preschool level (combining nonsymbolic as well as symbolic competencies), which are then put against the *secondary mathematical abilities* as taught in elementary school.

Mathematical abilities in elementary school

Several studies indicated that the aforementioned early numerical competencies predict later mathematics achievement in elementary school (e.g., Duncan et al., 2007; N. C. Jordan, Kaplan, Locuniak, & Ramineni, 2007; Powell & Fuchs, 2012). Whereas early numerical competencies seem to be universal, the secondary mathematical abilities acquired from elementary school onward are not. Although these abilities are culturally determined and highly dependent upon schooling practices (Geary, 1996, 2000), many similarities exist across nations and the same vital subcomponents seem often involved in adequate mathematical development in elementary school (Geary, 2000). Based on the literature of mathematical development in both typically achieving children and children with MLD, one can gain insight into different domains of mathematics that are essential for adequate mathematical functioning. Accordingly, four important domains of mathematics can be distilled from the work of Geary (2000, 2004): procedural calculation, number fact retrieval, word problems, and visuospatial abilities.

Procedural calculation is needed when solving arithmetic problems, converting numerical information into mathematical equations and algorithms (Dowker, 2005). The computational procedures are necessary in understanding the base-10 system and to solve more complex arithmetic problems (Geary, 2000). By executing arithmetic problems repetitively, basic number facts are retained in long-term memory and automatically retrieved if needed, termed as *number fact retrieval* (Dowker, 2005).

Elementary school children are expected, with sufficient practice, to memorize most basic arithmetic facts (Geary, 2000). Problems with procedural calculation and number fact retrieval fit in the postulation of two subtypes of MLD that has been made by several authors. The procedural subtype is characterized by frequent errors in the execution of procedures, the use of developmentally immature procedures to solve simple mathematical problems, a poor understanding of procedural concepts, and problems with the sequencing of multiple steps within procedures (Geary & Hoard, 2005; Pieters et al., 2013). The semantic memory subtype is characterized by problems in number fact retrieval and automatization (Geary, 1993, 2004; Mazzocco, Devlin, & McKenney, 2008; Pieters, Roeyers, Rosseel, Van Waelvelde, & Desoete, 2013; Wilson, Revkin, Cohen, Cohen, & Dehaene, 2006).

The domain of *word problems*, hereafter referred to as *word/language problems,* is associated with verbal problem solving abilities (Geary, Saults, Liu, & Hoard, 2000; Meyer, Salimpoor, Wu, Geary, & Menon, 2010). Although very simple word/language problems can even be solved by preschoolers, the complexity of the presented word/language problems increases greatly with age, eventually involving multistep problems needing the translation and integration of multiple verbal representations into mathematical representations (Geary, 2000). Children with MLD demonstrate a poor performance on word/language problem solving, perhaps because of difficulties with identifying the problem type or with the translation and integration of representations (Gonzalez & Espinel, 2002). Over time, word/language problems or contextual problems have gained importance in the mathematics curriculum (Kilpatrick, Swafford, & Findell, 2001). The *realistic mathematics education*, closely related to the principles of the *constructivistic learning theory* (Gravemeijer, 1994; Gravemeijer & Terwel, 2000), has led to an educational reform with an emphasis on mathematical problems in a more or less realistic problem situation (Hickendorff, 2013). Together with this evolution, the role of language in mathematics was investigated more extensively (Hickendorff, 2013; Negen & Sarnecka, 2012; Praet, Titeca, Ceulemans, & Desoete, 2013). Recent research suggests that general language relates to early numeracy and that specific math language mediates this relationship (Toll, 2013), therefore suggesting the importance of assessing math language, next to calculation and number facts.

When considering the three aforementioned domains, we can remark a parallel with the stipulations of the *DSM-5* (APA, 2013), in which the domains of procedural calculation, number fact retrieval, and verbal reasoning are also mentioned as being impaired in children with MLD.

Finally, in addition to these three domains, Geary (2004) mentioned that the domain of *visuospatial abilities* has an important supportive role in many mathematical competences. One of the competences on which visuospatial aspects have a substantial impact are *time-related competences* (e.g., Burny, 2012; Eden, Wood, & Stein, 2003; Freedman, Leach, & Kaplan, 1994). Time-related competences are defined as the abilities associated with measuring or recording time and incorporate aspects such as clock reading, calendar use, and measuring of time intervals (Burny, Valcke, & Desoete, 2009). Next to procedural knowledge and knowledge of mathematical facts, visuospatial abilities are indeed an additional key component in clock reading (Burny, Valcke, & Desoete, 2012). Although not agreed on by all studies (Landerl et al., 2004; Rousselle & Noël, 2007), the existence of a visuospatial subtype of MLD has been posited, next to the procedural and semantic memory subtype (Geary, 1993, 2004; Geary & Hoard, 2005; Karagiannakis, Baccaglini-Frank, & Papadatos, 2014). Visuospatial deficits can be associated with difficulties in clock reading, because the understanding of spatial clockwise movements and the differentiation of upper versus lower or left versus right are pivotal features for telling time correctly (Burny et al., 2012). As such, a growing body of evidence demonstrates that children with MLD experience difficulties in telling time (Andersson, 2008; Burny et al., 2012).

Before focusing on the early numerical competencies and mathematical abilities of children with ASD, it is important to note an upcoming recommendation in math literature. Recent studies in the field of mathematics emphasize the importance of incorporating a multicomponential approach instead of applying only one math composite score or examining only one subcomponent of mathematics (J. A. Jordan, Mulhern, & Wylie, 2009; Mazzocco, 2009; Simms, Cragg, Gilmore, Marlow, & Johnson, 2013). This suggestion fits with the statement of Dowker (2005) that there is no unitary mathematical construct. However, very few studies have combined several early numerical competencies or domains of mathematics within one study in the past (Praet et al., 2013). Certainly, research taking into account a multicomponential approach could shed light onto specific profiles of mathematical functioning in a much more fine-grained way (J. A. Jordan et al., 2009).

EARLY NUMERICAL COMPETENCIES AND MATHEMATICAL ABILITIES IN CHILDREN WITH AUTISM SPECTRUM DISORDER

Not surprisingly, the domain of social-communicative functioning has drawn by far the most attention in research on ASD, as it is a core feature of the disorder and a main target for intervention (e.g., Bohlander, Orlich, & Varley, 2012; Myles & Simpson, 2001). Despite this predominant clinical focus on the social-communicative impairments, interest in the academic functioning of children with ASD has grown more recently (Tincani, 2007; Wei, Christiano, Yu, Wagner, & Spiker, 2014; Whitby & Mancil, 2009). The issue of educational inclusion is currently a hot topic (e.g., Ferguson, 2008; Humphrey, 2008; Humphrey & Lewis, 2008), because a growing number of children with ASD tries to attend a mainstream educational setting. The fact that these children are subject to the same academic standards as their typically developing peers urges the need to gain insight into the academic strengths or needs of children with ASD. A large part of children with ASD are defined as high-functioning (i.e., displaying an IQ score of at least 70) and are therefore considered to be academically able to function successfully in mainstream schools. However, despite these IQ scores, these children still seem to experience difficulties, making appropriate support or accommodation still necessary to reach their full potential (Keane, Aldridge, Costley, & Clark, 2012; Whitby & Mancil, 2009). As such, teachers face a difficult challenge to assess the academic strengths and weaknesses of this particular group of children as well as to find appropriate techniques to educate these students (Kagohara, Sigafoos, Achmadi, O'Reilly, & Lancioni, 2012; Whitby & Mancil, 2009). Whereas this concern has resulted in a growth of the literature on language (e.g., Kjelgaard & Tager-Flusberg, 2001), literacy (e.g., Jacobs & Richdale, 2013), and cognitive profiles (e.g., Ankenman, Elgin, Sullivan, Vincent, & Bernier, 2014), the field of mathematics still remains a rather unexplored topic. Although teachers and therapists often consider mathematics as one of the stumbling blocks in the educational curriculum of children with ASD (Department for Education and Skills, 2001; van Luit, Caspers, & Karelse, 2006), the amount of scientific research on this topic does not match this concern. Before going into a full consideration of the few existing studies on this topic, the most important cognitive theories of ASD will be described along with their possible impact upon mathematical performance.

Cognitive theories of autism spectrum disorders

Three major cognitive theories dominate the psychological research into ASDs (Rajendran & Mitchell, 2007). Previous research already demonstrated that the autism-specific cognitive profile may impact upon academic performance (Fleury et al., 2014). Whether these cognitive theories can also be applied to explain in particular the mathematical profiles of children with ASD remains questionable, because research connecting these two topics is scarce. Nevertheless, the few studies linking these fields are mentioned below. In addition, we also tried to extrapolate some findings in children with MLD to children with ASD, since the cognitive deficits in MLD and ASD seem to hold some similarities.

The *theory of mind* (*ToM*) hypothesis was formulated in the mid 80s, postulating that individuals with ASD have difficulties with attributing mental states to self and others in order to understand and predict behavior (Baron-Cohen, Leslie, & Frith, 1985). This impairment in mind-reading was considered as a primary cognitive deficit causing several core characteristics of ASD, such as social and communication impairments (Baron-Cohen, Tager-Flusberg, & Cohen, 1993). Given its strong involvement in social-communicative deficits, it seems unlikely to deduce large consequences from this theoretical account for the domain of mathematics. However, one could assume an impact of ToM abilities on mathematical exercises involving perspective-taking, such as mathematical word/language problems. Frith and Happé (1996) hypothesized for example that difficulties with ToM in children with ASD would lead to less deceit for mathematical word/language problems, because of a smaller urgency to read the speaker’s mind. However, one could also assume a weaker performance on exercises urging a correct use of mental state terms.

The *theory of executive dysfuntion* postulates, as opposed to the ToM hypothesis, a domain-general cognitive deficit (Rajendran & Mitchell, 2007). Ozonoff, Pennington, and Rogers (1991) defined executive function as a mental control process used to maintain an appropriate problem-solving set for attainment of a future goal. Executive function is considered as an umbrella term for several functions including working memory, inhibition, planning, cognitive flexibility/set shifting, and fluency/generativity. It has been proposed that the behavioral features of ASD emerge from problems in executive functions (Hill, 2004; Ozonoff et al., 1991; Russo et al., 2007). Because one of the aetiological cognitive factors supposedly contributing to MLD constitutes of deficits in executive functions (e.g., Andersson & Ostergren, 2012; Geary, Hoard, Nugent, & Bailey, 2012), one might also expect to observe mathematical problems in children with ASD. Impairments in working memory have proven to play a role in number fact retrieval deficits (Geary, 1993; Geary, Hoard, Byrd-Craven, & DeSoto, 2004) and delayed procedural development (Geary, 1993, 2004). Although results are sometimes contradictory (Kolkman, Hoijtink, Kroesbergen, & Leseman, 2013), it has also been argued that problems with inhibition (Bull & Scerif, 2001), shifting (Kroesbergen et al., 2009), and naming speed/fluency (Geary, 2011a; Temple & Sherwood, 2002) are linked to mathematical abilities and disorders.

Finally, the *weak central coherence* (*WCC*) *theory* (Frith, 1989) does not only focus on deficits but also on assets of people with ASD in certain areas (Happé, 1999). According to the WCC account, individuals with ASD are hypothesized to have a cognitive style characterized by a processing bias for featural and local information, and a relative failure to extract global information (Frith & Happé, 1994). Although the theory has underwent some modifications since its original conception (see Happé & Frith, 2006 for an overview), several studies have suggested robust findings of a local bias in children with ASD (Happé & Frith, 2006). Regarding the field of mathematics, the WCC theory has been linked to verbal subitizing in children with ASD. Several studies suggested that children with ASD, due to a weaker central coherence, use a serial counting strategy rather than a subitizing process to enumerate small quantities (Gagnon, Mottron, Bherer, & Joanette, 2004; Jarrold & Russell, 1997). Moreover, it has been argued that children with ASD would show preserved procedural and mechanical skills, but impaired complex information processing abilities (Goldstein, Minshew, & Siegel, 1994; Minshew, Goldstein, Taylor, & Siegel, 1994), which has later been linked to the WCC framework (Noens & van Berckelaer-Onnes, 2005). However, these latter findings adhered mainly to literacy and have not yet been demonstrated for the field of mathematics (Goldstein et al., 1994; Minshew et al., 1994).

A detailed discussion of the aforementioned theories as well as some other cognitive factors, such as the assumed IQ discrepancy profiles in children with ASD (e.g., Ankenman et al., 2014; Siegel, Minshew, & Goldstein, 1996), falls beyond the scope of this dissertation. It is, however, important to recognize that these cognitive factors might have an influence (both negative or positive) on mathematical performance.

Research on early numerical competencies or mathematical abilities in children with autism spectrum disorder

Although practitioners often report difficulties with mathematics in children with ASD, several anecdotal and descriptive reports provide evidence for greater proficiency in mathematics in individuals with ASD (Baron-Cohen, Wheelwright, Burtenshaw, & Hobson, 2007; Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001; McMullen, 2000; Sacks, 1986; Smith 1983; Ward & Alar, 2000). Baron-Cohen et al. (2001) demonstrated for example that scientists, and especially mathematicians, score higher on self-administered questionnaires for traits associated with the autism spectrum. In line with this finding, Baron-Cohen et al. (2007) reported a three- to sevenfold increase for autism spectrum conditions among mathematicians. In addition, some authors described anecdotal reports of quick and exact quantification abilities among individuals with ASD (e.g., Kelly, Macaruso, & Sokol, 1997; Sacks, 1986).

When turning to the empirical studies on mathematical abilities in children with ASD, we observe a paucity of research along with inconclusive results: Some studies show difficulties in mathematics, some find average mathematical abilities, still others suggest a strength in mathematics (see Chiang & Lin, 2007 for a review). One explanation might be the large heterogeneity observed in children with ASD, causing different mathematical profiles (Georgiades, Szatmari, & Boyle, 2013; Wei et al., 2014). However, another explanation stems from the fact that different approaches and research questions are handled within different studies, with some studies focusing on comorbidity, some on between-group differences, and others on within-group differences. Each of these categories of studies will be described in more detail below.

Comorbidity studies. Although varying considerably between studies, the prevalence of MLD in a general school-aged population is traditionally estimated at 2.27% to 14% (Barbaresi et al., 2005; Desoete et al., 2004; Shalev et al., 2005). A small number of comorbidity studies show that the prevalence of mathematical problems in children with ASD exceeds these figures. Mayes and Calhoun (2006) conducted a study in which the frequency of reading, math, and writing abilities was assessed in 949 children, aged 6 to 16 years, with various clinical disorders. They concluded that 23% of the children with ASD were diagnosed with a learning disability, now termed *learning disorder*, in math (Mayes & Calhoun, 2006). Although this number is smaller than the reported learning disorders in written expression and the condition is described as less severe than writing problems, this still remains a substantial subgroup of children. Reitzel and Szatmari (2003) conducted a longitudinal study in which they investigated the learning characteristics of 27 children with Asperger's Disorder (AD) and 30 children with high-functioning autism (HFA) at two different ages (6-8 years and 9-13 years). They concluded that 73% of the children with HFA and 35% of the children with AD had a general MLD, defined as a standard score below 80 on a mathematical achievement test (Reitzel & Szatmari, 2003). Moreover, 12% of the HFA group and 46% of the AD group had a specific MLD, which was defined as an IQ above 80 and a minimum of 15 points discrepancy with a mathematical achievement test (Reitzel & Szatmari, 2003).

Between-group differences. Between-group differences can be studied by comparing the mathematical abilities of children with ASD to those of a control group or to a normed population of typically developing children. Within this category, two lines of research can be identified: one focusing on outcomes and one on processes.

The first line of research focuses on mathematical outcomes, studying whether the mathematical performance of children with ASD is higher/lower compared to that of typically developing children. Chiang and Lin (2007) made a review on this topic. They included a total of 18 articles, which encompassed 837 individuals with AD or HFA, ranging from 3 to 51 years of age. When looking at the scores of the participants on standardized mathematical achievement tests, they concluded that the majority of them obtained scores well within the average range compared to the normed population (Chiang & Lin, 2007). After 2007, some additional studies focused on this topic. Iuculano et al. (2014) investigated the mathematical abilities of 18 children with ASD in comparison to 18 typically developing children, aged 7-12 years. They demonstrated that children with ASD have average abilities on mathematical reasoning (word and language based problems) and superior numerical problem solving abilities compared to typically developing peers. This conclusion was in line with previous descriptive research indicating average to good mathematical abilities in participants with ASD (Church, Alisanski, & Amanullah, 2000). In addition, Soulieres et al. (2010) conducted a case study on special abilities in autism spectrum conditions and reported that certain individuals with ASD may indeed develop superior and specialized abilities in estimation (operationalized as a magnitude comparison task). However, some studies suggest that regarding mathematics, children with ASD perform significantly worse than the general population. Wei et al. (2013) demonstrated that children with ASD (*n* = 549, age 7-17 years) had significantly lower scores on applied problems and calculation than the general population. Moreover, their math achievement grew more slowly than that of their peers in the general population in elementary school and that of students with a learning disorder on calculation (Wei et al., 2013). Wei et al. (2014) also found that their ASD group (*n* = 130, age 6-12 years) scored on average one standard deviation below the national average of children in the general population for mathematics.

The second line of research focuses on mathematical processes, studying whether children with ASD use different strategies to solve mathematical exercises than typically developing children. Jarrold and Russell (1997) suggested for example that children with ASD (*n* = 22, age 6-12 years) use a counting strategy for enumerating even a small amount of objects, whereas typically developing children use a subitizing strategy. Although it is possible that children with ASD may be able to subitize, apparently they do not use this strategy spontaneously. Gagnon et al. (2004) replicated this finding with a group of 14 high-functioning adolescents with ASD (aged 10-21 years), showing that, although no difference in outcome abilities was found between individuals with ASD and typically developing peers, different processes were used to come to the same solution. These findings have been linked to the WCC account (cf. supra; Gagnon et al., 2004; Jarrold & Russell, 1997). Finally, Iuculano et al. (2014) also reported a difference in strategy use between children with ASD en typically developing children. Children with ASD (*n* = 18, age 7-12 years) relied more frequently on sophisticated decomposition strategies than their typically developing peers (Iuculano et al., 2014).

Within-group differences. A criticism on the aforementioned between-group studies implies the fact that group-level findings may mask different subgroups of children with ASD (Jones et al., 2009; Wei et al., 2014). Therefore, several studies examined the mathematical abilities of children with ASD relative to their own cognitive abilities. Although most children tend to obtain mathematical scores that are in line with other cognitive domains of functioning (Mayes & Calhoun, 2008), a substantial number of children shows a relative strength or weakness in the domain of mathematics (Jones et al., 2009). However, up till now, it remains unclear which subgroup constitutes the largest one. Jones et al. (2009), for example, demonstrated a larger discrepancy between IQ and mathematical abilities compared with other abilities – such as reading – in 14- to 16-year-olds with ASD (*n* = 100). According to these authors, mathematics can considered to be a strength, as 16.2% of the individuals with ASD in their sample showed a relative strength in mathematics whereas only 6.1% of them demonstrated a relative weakness (Jones et al., 2009). In contrast, Mayes and Calhoun (2003) analyzed intelligence, cognitive, and academic profiles in a sample of 116 children with ASD (3 – 15 years) and assumed mathematics to be a relative weakness, as 22% of the high-functioning school-aged (6-15 years) cases showed significantly weaker mathematical abilities compared to general IQ. The review of Chiang and Lin (2007) also concluded that the mathematical ability of individuals with ASD is relatively lower than their intellectual ability. However, these authors considered the clinical significance of this finding to be small and pointed out that some individuals with ASD are even mathematically gifted (Chiang & Lin, 2007). Regarding the youngest age group (3-7 years), Mayes and Calhoun (2003) found no significant differences between IQ and math scores.

Although pioneering in this research topic, the above-mentioned studies suffer from some shortcomings. First, none of these studies has focused explicitly on the important developmental period of preschool age. Because in typically developing children early numerical competencies in preschool are predictive for later mathematics in elementary school (N. C. Jordan & Levine, 2009; Kroesbergen et al., 2012; Navarro et al., 2012; Passolunghi & Lanfranchi, 2012), studying precursors that serve as a foundation for later mathematics performance can be informative in children with ASD. Research focusing on this aspect could possibly reveal potential risk factors or strengths (that can reveal protective factors) and contribute to the early identification of children with mathematical problems or talents. The early identification of problems may, in turn, lead to early intervention, which has already proven to be helpful in reducing the mathematics gap (Berch, 2005; Bryant et al., 2011; Fuchs et al., 2005). Second, most of the studies fail to account for the componential nature of mathematics, including just one aspect of mathematics or one component score (Chiang & Lin, 2007; Gagnon et al., 2004). Only the more recent studies start to include the large subcomponents of standardized math achievement tests in order to describe possible differential effects of mathematical functioning (Iuculano et al., 2014; Wei et al., 2014). Because recent studies in the field of MLD emphasize the importance of incorporating a multicomponential approach (J. A. Jordan et al., 2009; Mazzocco, 2009; Simms et al., 2013), it will be important to include several components simultaneously. After all, the use of global composites can mask patterns of strengths and weaknesses (Minshew et al., 1994). Finally, most of the studies are cross-sectional in nature; longitudinal studies on mathematical abilities in children with ASD are only in its infancy. The studies of Wei et al. (2013) and Wei et al. (2014) are the first to provide growth trajectories of mathematics in children with ASD. However, no study has focused on the predictive value of several preschool competencies for later mathematics in elementary school as yet.

This dissertation lays its main focus on a between-group perspective by comparing the performance of children with ASD to that of typically developing children. Albeit acknowledging the importance of within-group studies, this does not detract the value of between-group approaches. The examination of group-level differences at different ages may have its own merit, because the emergence of differences despite the large heterogeneity may demonstrate the power of the results and can provide information on particular academic profiles that are common in children with ASD.

RESEARCH OBJECTIVES AND OUTLINE OF THIS DISSERTATION

Practitioners' reports indicate the presence of mathematical difficulties in children with ASD (Department for Education and Skills, 2001; van Luit et al., 2006). However, the amount of research on this topic does not match their concern, resulting in a poor insight into the level of early numerical competencies or mathematical abilities in this group of children.

In this doctoral dissertation, we wanted to apply a between-group approach by comparing the early numerical competencies and mathematical abilities of children with ASD to those of typically developing children. More specifically, we had the intention to provide an exploratory analysis of possible differences in early numerical competencies or mathematical abilities between both groups of children. By doing so, we tried to provide a first step to unravel the inconclusive results on this topic, as well as to support practitioners in their quest for answers.

This doctoral thesis had three main goals. First, we aimed at exploring the performance profile on early numerical competencies of children with ASD to that of typically developing children at preschool level (*Chapter 2*, *Chapter 3*, and *Chapter 5*). Second, we compared the performance of children with ASD and typically developing children on four important domains of mathematics in elementary school (*Chapter 4* and *Chapter 5*). Finally, we investigated the predictive value of early numerical competencies in preschool for the domains of mathematics in elementary school and explored whether children with ASD and typically developing children do or do not hold a similar pattern of results (*Chapter 5*).

Chapter 2 presents the results of a study in which we compared the early numerical competencies of children with ASD and typically developing children at a moment at which little attention is paid to numbers within the Flemish curriculum, namely, the second year of preschool (4 to 5 years of age).

Chapter 3 continues this line of reasoning and consists of a study in which the early numerical competencies were compared at a moment at which numbers become increasingly integrated within the educational curriculum, in order to prepare children to start the first grade of elementary school. As such, all children were examined in the third year of preschool, at 5 to 6 years of age.

Chapter 4 constitutes a larger sample of elementary school children with ASD attending first to fourth grade of mainstream educational settings. Their performance on four domains of mathematics was compared to the scores of the normed samples of the standardized tests that were administered. With increasing age, factors such as teaching materials/methods and the increasing demands and complexity of mathematical knowledge may provide different results compared to the performance profiles of younger children.

Chapter 5 presents a longitudinal study focusing on the transition period from preschool to first grade. This study aimed at investigating the predictive value of the early numerical competencies in preschool for the four domains of mathematics in first grade. The pattern of results in children with ASD was compared to the one found in a typically developing group.

Chapter 6 provides an overview and general discussion of the most important findings. Furthermore, limitations and implications for future research and practice are given.

It should be noted that the chapters in this dissertation correspond to individual manuscripts that are accepted for publication (*Chapter 5*), under editorial review (*Chapters 2* and *3*), or submitted for publication (*Chapter 4*). Chapters may therefore partially overlap as each manuscript should be able to stand on its own.

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APPENDIX

Within the literature on mathematical abilities in children, a wide variety on concepts is used to define the early numerical competencies in preschool or the mathematical abilities in elementary school. In addition, not only the terms used to describe the concepts differ among studies, but also the exact operationalizations of them. Because this variation may be responsible for differences in findings and conclusions, we deemed it important to provide a detailed description of the concepts and tasks used in this doctoral dissertation. Figure 1 provides a summary of the included concepts, along with the concepts originally provided in the framework of Jordan and Levine (2009) and Geary (2000, 2004).

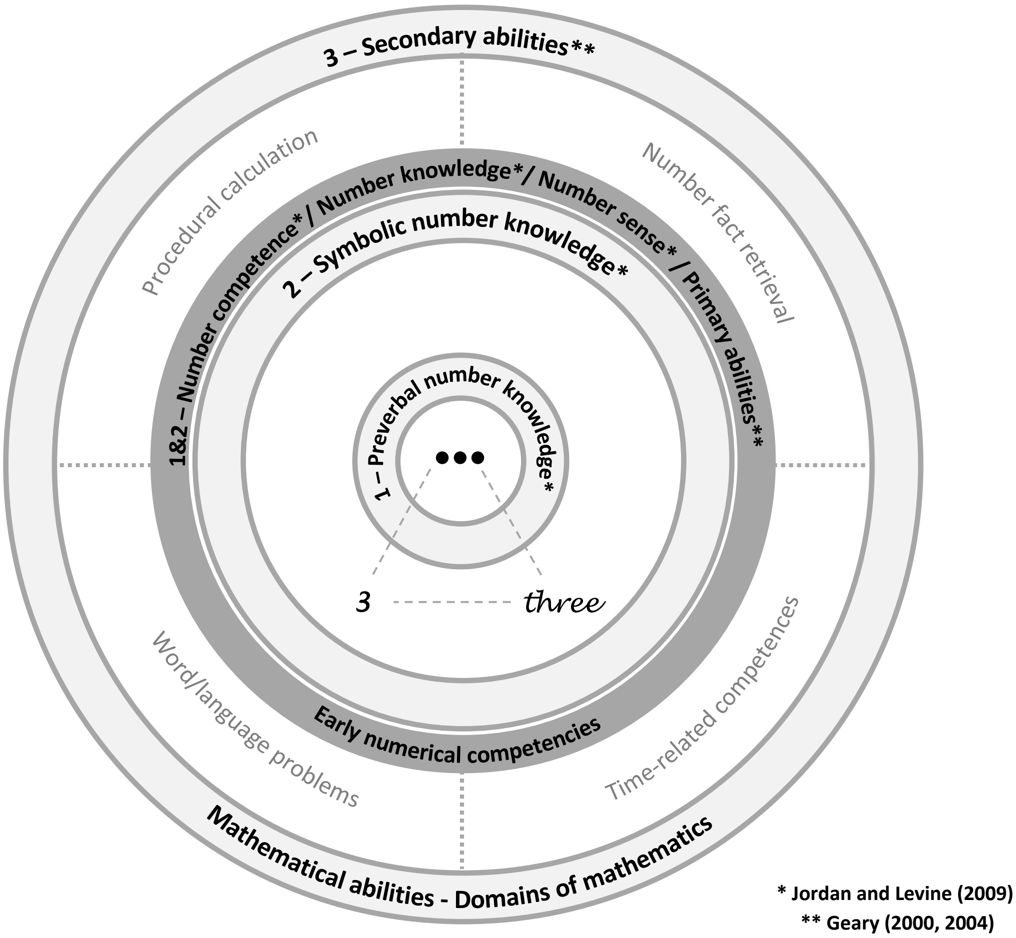


Figure 1. Summary of the key concepts of this dissertation in relation to existing frameworks.

Early numerical competencies in preschool

Verbal subitizing. The preschoolers' verbal subitizing abilities were tested by means of a computerized enumeration task similar to the one described by Fischer, Gebhardt, and Hartnegg (2008) and based on the stimuli used by Maloney, Risko, Ansari, and Fugelsang (2010). In this task, black squares on a white background were displayed on a 17 inch monitor. Responses were collected using a voice key and were manually put in by the researcher. Each trial began with a central fixation point presented for 500 ms. A display containing one to nine square boxes was then centrally presented at fixation until a vocal response was detected. Participants were instructed to say aloud the number of squares on the screen as quickly and accurately as possible. The individual area, total area, and density of the squares were varied to insure that participants could not use non-numerical cues to make a correct decision (see Dehaene, Izard, & Piazza, 2005; Maloney et al., 2010). There were two practice phases and one test phase. In the first practice phase, the child was presented with five displays of randomly chosen numerosities (varying between one and nine) with a presentation and response time of 5,000 ms, so the stimulus remained visible during response time. The second practice phase consisted of 10 displays of randomly chosen numerosities (varying between one and nine) with a presentation time of 120 ms – in line with the study of Hannula, Räsänen, and Lehtinen (2007) and Fischer et al. (2008) – and a mask of 100 ms. Participants had a total response time of 4,000 ms from presentation of the stimulus onward. The test phase consisted of 72 trials (each numerosity of one to nine was presented eight times) with a presentation time of 120 ms, a mask of 100 ms, and a total response time of 4,000 ms. The short presentation time prevented children from counting the squares to enumerate the items (see Fischer et al., 2008). Both accuracy (% correct) and mean reaction times (based on correct trials only) were used as outcome variables. Figure 2 provides an illustration of a test trial of the enumeration task.

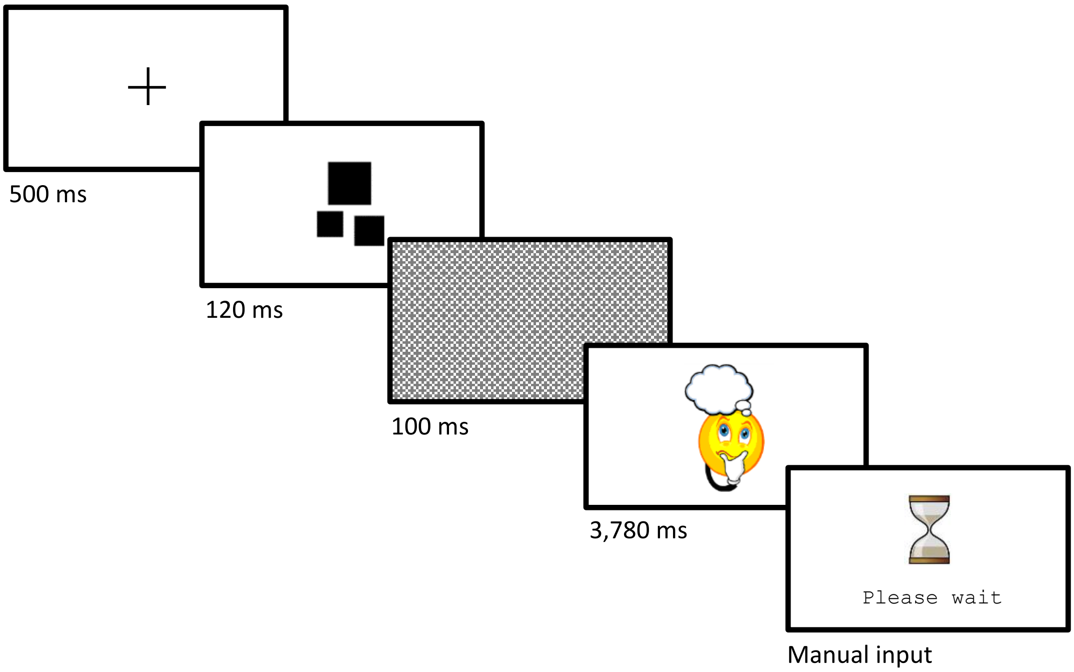


Figure 2. Verbal subitizing – Test trial of the enumeration task.

Counting. Counting abilities were assessed using two subtests of the *Test for the Diagnosis of Mathematical Competencies* (*TEDI-MATH*; Grégoire, Noël, & Van Nieuwenhoven, 2004), a Belgian individual assessment battery constructed to detect mathematical problems from the second year of preschool until the third grade in elementary school. The psychometric value of the battery was tested on a sample of 550 Dutch-speaking Belgian children (Grégoire, 2005) and the *TEDI-MATH* has proven to be a conceptually accurate and clinically relevant instrument (Desoete & Grégoire, 2006; Stock, Desoete, & Roeyers, 2007), and its predictive value has been demonstrated in several studies (Desoete & Grégoire, 2006; Desoete, Stock, Schepens, Baeyens, & Roeyers, 2009). Procedural counting (subtest 1) was assessed using accuracy in counting row and counting forward to an upper bound and/or from a lower bound. The task consisted of eight items and had a maximum raw score of 8. Conceptual counting (subtest 2) was assessed by judging the validity of counting procedures based on the five basic counting principles formulated by Gelman and Gallistel (1978). In order to investigate these principles, children had to judge the counting of both linear and nonlinear patterns of objects, and were asked some questions about the counted amount of objects. Furthermore, they had to construct two numerically equivalent amounts of objects and had to use counting as a problem-solving strategy in a riddle. The maximum total raw score for this subtest was 13. Raw scores were converted into percentages of correct trials as outcome variables. Table 1 provides some examples of the exercises.

Table 1. *Counting – Sample exercises of procedural and conceptual counting tasks*

Procedural counting	*Conceptual counting*
"Count up to 6"	"Count all objects" – "How many objects are there in total" – "How many objects are there if you start counting with the leftmost object in the array" – "How many objects did I hide"
"Count from 3"	"Put as many objects on this board as there are on this one"
"Count from 5 up to 9"	"Here you can see some snowmen wearing a hat" – After taking away all the hats and putting them underneath a box, the experimenter asks: "How many hats are there covered under this box"

Magnitude comparison. A computerized magnitude comparison task based on the work of Halberda and Feigenson (2008) and Inglis, Attridge, Batchelor, and Gilmore (2011) was used to test this early numerical competency. In each trial, two displays of black dots on a white background were presented simultaneously on a 17 inch monitor. On top of the two displays, an illustration of a sun and a moon were presented. Participants were instructed to press the sun- or the moon-button corresponding to the largest numerosity on a response box as quickly and accurately as possible. Six different ratios were presented. When dividing the smallest by the largest numerosity, these ratios were: .33, .50, .67, .75, .80, and .83. Different numerosities (e.g., 1 vs. 2, 2 vs. 4 …) were used to operationalize each ratio (e.g., .50).The individual area, total area, and density of the squares were varied to insure that participants could not use non-numerical cues to make a correct decision (see Dehaene et al., 2005). There were two practice phases and one test phase. In the first practice phase, the child was presented with five trials of randomly chosen numerosities with a presentation time of 5,000 ms, a mask of 1,000 ms, and a total response time of 6,000 ms. The presentation of the stimuli was preceded by a display with two fixation crosses lasting for 500 ms. The second practice phase consisted of 10 displays of randomly chosen numerosities with a fixation time of 500 ms, a presentation time of 1,200 ms, a mask of 2,800 ms, and a total response time of 4,000 ms from presentation onward. In between trials, a blank screen appeared for 500 ms. The test session consisted of 72 trials (each ratio was presented twelve times) with a fixation time of 500 ms, a presentation time of 1,200 ms, a mask of 2,800 ms, and a total response time of 4,000 ms. Both accuracy (% correct) and mean reaction times (based on correct trials only) were used as outcome variables. Figure 3 provides an illustration of a test trial of the magnitude comparison task.

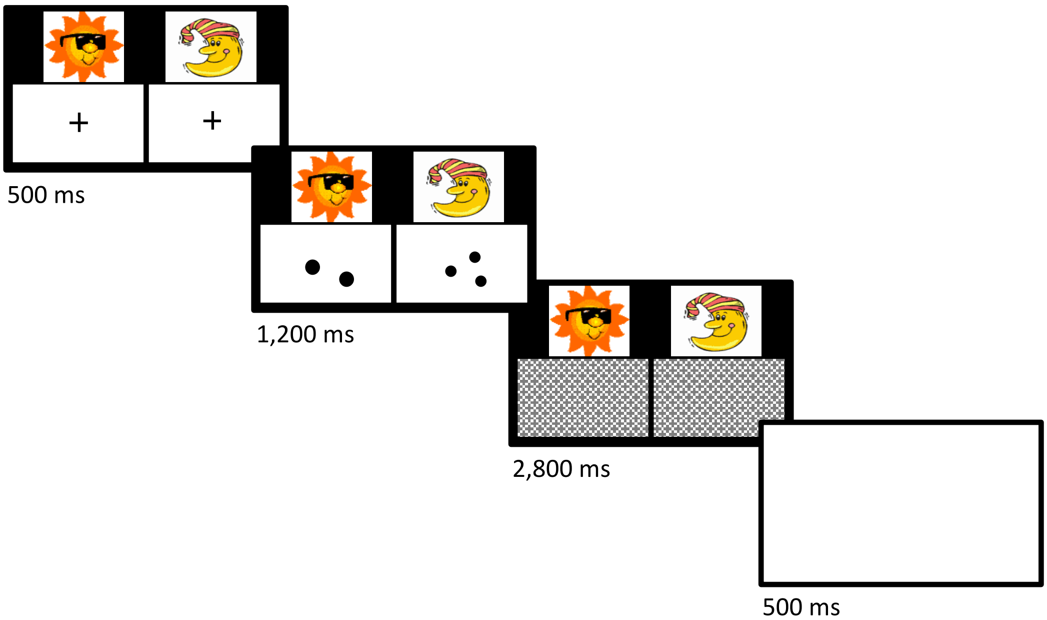


Figure 3. Magnitude comparison – Test trial of the magnitude comparison task.

Estimation. Estimation was tested by means of a number line task based on the task of Siegler and Opfer (2003) and Siegler and Booth (2004). Two different versions were used: a 0-10 number line was presented in the second year of preschool, a 0-100 number line task was administered in the third year of preschool. For all trials – independent of the version that was used – children were presented with 25 cm long lines in the center of white A4 sheets. Each line was seen separately from the others. The left end anchor of the number line was labeled by 0 and the right anchor by 10 or

100. The number to be positioned appeared 2 cm above the center of the line. Stimuli were presented in three different formats. In the visual Arabic format, stimuli were presented as Arabic numerals (e.g., anchors 0 and 10/100, target number 2); target numbers were not read out. In the auditory-verbal format, stimuli were presented as spoken number words (e.g., anchors zero and ten/hundred, target number two), and in the analog magnitude format, stimuli were presented as dot patterns (e.g., anchors of zero dots and ten/hundred dots, target number two dots). The dot patterns consisted of black dots in a white disc. Dot patterns were controlled for perceptual variables using the procedure of Dehaene et al. (2005), meaning that on half of the trials the dot size was held constant, while on the other half, the size of the total occupied area of the dots was held constant. Figure 4 provides an example of a trial in the three different presentation formats.

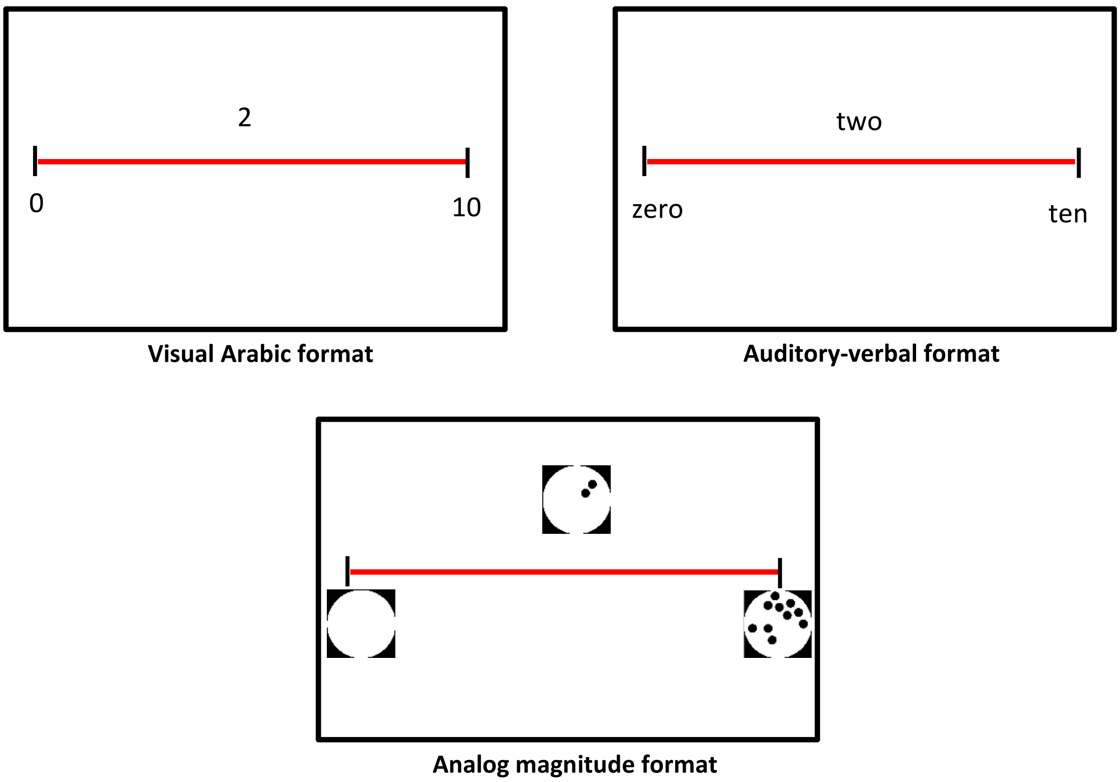


Figure 4. Estimation – Test trial of the 0-10 number line task in the three presentation formats.

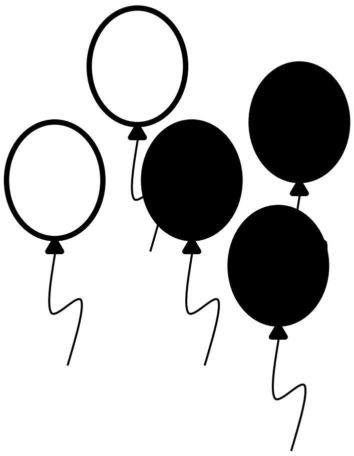
When composing the task, both the format as well as the presented numerosities were chosen randomly. However, once determined, this order was the same for each participant. Children were asked to put a single mark on the line to indicate the location of the number. Although the instructions could be rephrased if needed, no feedback was given to the participants regarding the accuracy of their marks. The 0-10 number line task consisted of three practice trials (for which the numerosities were randomly chosen between 1 and 9) and 27 test trials in which each numerosity from 1 to 9 was presented as a target number in all three presentation formats. The 0-100 number line consisted of three practice trials (for which the numerosities were randomly chosen between 1 and 99), and 30 test trials using the following 10 target numbers in all three presentation formats: 2, 3, 4, 6, 18, 25, 42, 67, 71, and 86 (corresponding to sets A and B in Siegler & Opfer, 2003). The percentage of absolute error (PAE) was calculated per child as a measure of estimation accuracy, following the formula of Siegler and Booth (2004):

$$\text{PAE} = \left|\frac{\text{Estimate} - \text{Estimated Quantity}}{\text{Scale of Estimates}}\right| \text{ x } 100$$

For example, when a child puts a mark at 65 on a 0-100 number line when asked to situate 50, the PAE is [65 – 50) / 100] x 100 = 15%.

Next to PAE, the underlying representation (linear or logarithmic) of the estimates was also investigated. In order to do this on group level, the procedure of Siegler and Opfer (2003) was used. Regression analyses on the group median estimates (plotting median estimates against the actual to be estimated values) were used to compute both linear and logarithmic fits (R^2 values). The difference between the linear and logarithmic regression models was tested with a paired samples t-test. First, the absolute difference between the median estimate for each number and the predicted values based on the linear and logarithmic model respectively was calculated, resulting in the absolute values of the residuals of the linear and logarithmic fit. Next, the paired samples t-test was executed to determine if the absolute values of the residuals of the linear and logarithmic fit differed significantly from each other. On individual level, following the procedure of Berteletti, Lucangeli, Piazza, Dehaene, and Zorzi (2010), each child was attributed the best fitting significant model between linear and logarithmic. A child was classified as not having a valid representation when both linear and logarithmic coefficients failed to reach significance or when slopes were negative (indicating an inverse relationship as the one to be expected).

Arithmetic operations. Arithmetic operations were assessed using a subtest of the *TEDI-MATH* (Grégoire et al., 2004). A series of six visually supported addition and subtraction exercises was presented to all children (subtest 5.1). The maximum total raw score was 6. The raw score was converted into a percentage of correct trials as outcome variable. Figure 5 provides an example of a simple visually supported addition exercise.



"Here you see two white balloons and three black balloons."

"How many balloons are there together?"

Figure 5. Arithmetic operations – Example of a simple addition exercise.

Mathematical abilities in elementary school

Procedural calculation. The procedural calculation abilities were tested using a subtest of the *Cognitive Developmental Skills in Arithmetics* (*Cognitieve Deelhandelingen van het Rekenen* [*CDR*]; Desoete & Roeyers, 2006). For a detailed description of the *CDR*, we refer to Desoete and Roeyers (2005). The *CDR* is a 90-item test that embraces different subskills, including procedural abilities (*P*-tasks). The *P*-tasks comprise 10 mathematical procedural problems, such as number splitting and addition/subtraction by regrouping exercises, presented in a number problem format; for example "12 – 9 = __". The *CDR* consists of three parallel test versions: grade 1-2, grade 3-4, and grade 5-6. The score on procedural calculation was defined as the total accuracy expressed as a z-score using the mean and standard deviation of the normed sample of the test.

Number fact retrieval. The *Arithmetic Number Facts Test* (*Tempotest Rekenen* [*TTR*]; De Vos, 1992) is a numerical facility test assessing the memorization and automatization of arithmetic facts. The *TTR* consists of five subtests concerning arithmetic number fact problems: addition, subtraction, multiplication, division, and mixed exercises. Participants were instructed to solve as many items as possible in five minutes; they could work one minute on every subtest. The score on number fact retrieval was defined as the total accuracy expressed as a z-score using the mean and standard deviation of the normed sample of the test. In first and second grade, the assessment was limited to the addition and subtraction exercises, as multiplications and divisions are only practiced and mastered at the end of second grade. Figure 6 provides an extract of the exercises of the *TTR*.

Addition	**Subtraction**	**Multiplication**	**Division**	**Mixed**
1+1 =___	2-1 =___	1x4 =___	4:2 =___	2+1 =___
2+1 =___	3-2 =___	2x2 =___	5:1 =___	2-1 =___
3+0 =___	4-2 =___	1x7 =___	12:2 =___	2x5 =___
4+1 =___	3-0 =___	0x5 =___	15:3 =___	4:2 =___
2+3 =___	5-2 =___	8x1 =___	10:5 =___	3+2 =___

Figure 6. Number fact retrieval – Extract from the exercises. Adapted from *Tempo Test Rekenen (TTR) [Arithmetic Number Facts Test]*, by T. De Vos, 1999, Nijmegen: Berkhout.

Word/language problems. The word/language problem abilities were tested using three subtests of the *CDR* (Desoete & Roeyers, 2006): linguistic abilities (one-sentence mathematical problems in a word problem format, e.g., "1 more than 5 is__", *L*-tasks); mental representation abilities (one-sentence mathematical problems that go beyond a superficial approach of keywords and that require a mental representation to prevent errors, e.g., "47 is 9 less than __", *M*-tasks); and contextual abilities (more-than-one-sentence mathematical problems in a word problem format, e.g. "Wanda has 47 cards. Willy has 9 cards less than Wanda. How many cards does Willy have?", *C*-tasks). As such, the word/language problems component was assessed by different subtests in order to differentiate between simplicity (*L*) versus complexity (*C*), and items with (*M*) versus without (*L*) mental representation involved. Figure 7 illustrates the need for mental representation to correctly solve the *M*-tasks (whereas this is no necessity for correctly solving the *L*-tasks). The score on word/language problems was defined as the total accuracy expressed as a z-score using the mean and standard deviation of the normed sample of the test.

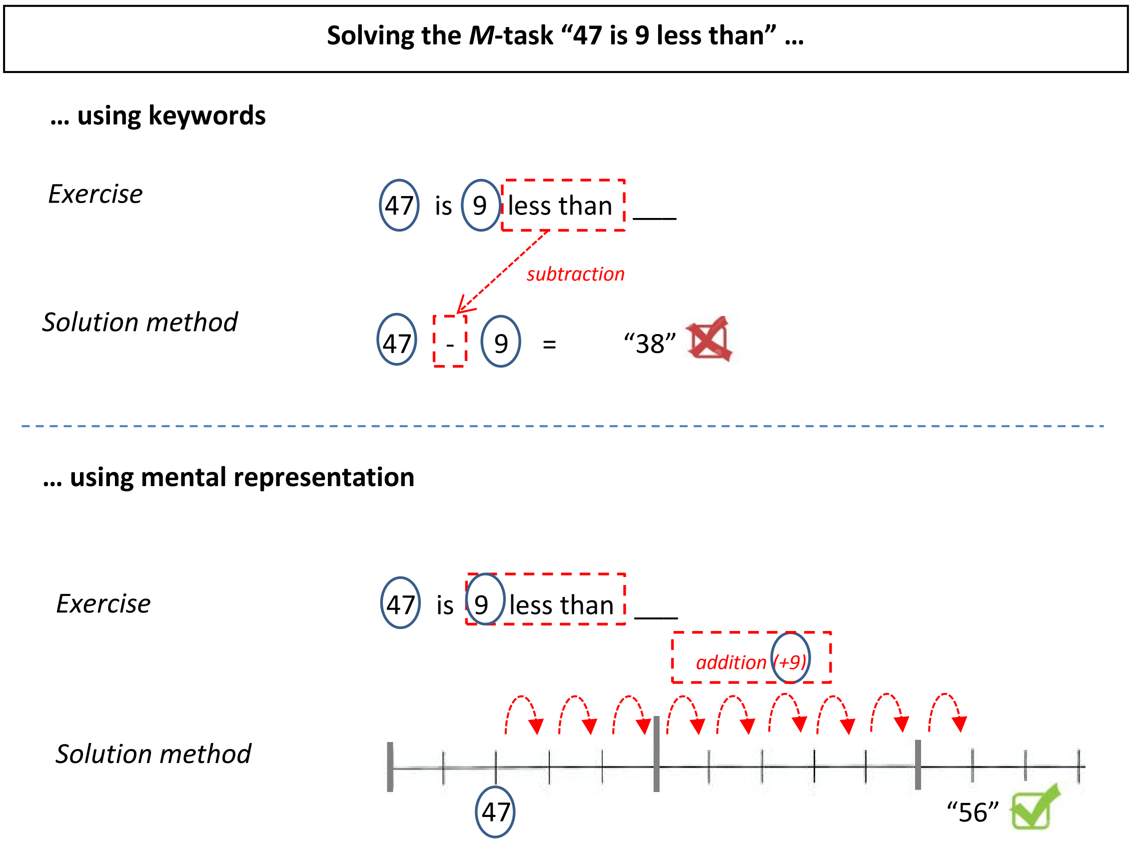
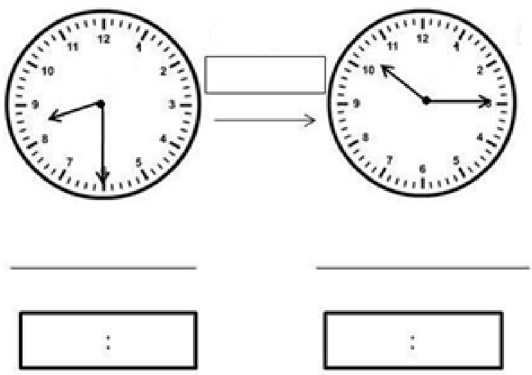


Figure 7. Word/language problems – Using keywords versus mental representation when solving a mental representation task (*M*-task).

Time-related competences. *The Time Competence Test (TCT; Test Tijdscompetentie*; Burny, 2012; Burny, Valcke, & Desoete, 2012) is a test battery developed to assess the mastery of time-related competences in elementary school children. The test consists of four domains: clock reading, time intervals, time-related word problems, and calendar use. The *TCT* consists of four parallel tests that are associated with the ability levels in each grade (grade 1, grade 2, grade 3, and grade 4-6). The items are each time based on the Flemish elementary mathematics curriculum of the specific grade(s). The *TCT-1* includes 14 items, the *TCT-2* includes 16 items, the *TCT-3* includes 33 items, and the *TCT-4-6* contains 32 items. The score on time-related competences was defined as the total accuracy expressed as a z-score using the mean and standard deviation of the normed sample of the test. Figure 8 provides an extract from the exercises of the *TCT-3*.

Clock reading and time intervals



What time is it? Write down the time in words on the line and indicate the corresponding time on the digital clock.

Afterwards, calculate how many hours and minutes have passed between the two clocks and write down your answer in the box above the arrow.

Time-related word problems

Mom is baking a cake. She puts the cake in the oven at a quarter past ten. The cake has to bake for 45 minutes. At what time does mom has to put the cake out of the oven? ____

Calendar use

Augustus 2010

Week		Di	Wo	Do	Vr	Za	Zo
30							1
31	2	3		5	6	7	8
32	9	10	11	12	13	14	15
33	16	17	18	19	20	21	22
34	23	24	25	26	27	28	29
35	30						

Fill out the empty boxes on the calendar and answer the following questions.

e.g., August counts __ days.

Figure 8. Time-related competences – Extract from the exercises.
Adapted from *Time-related competences in primary education (Doctoral dissertation)*, by E. Burny, 2012, Ghent: Ghent University.

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CHAPTER 2

EARLY NUMERICAL COMPETENCIES IN 4- AND 5-YEAR-OLD CHILDREN WITH AUTISM SPECTRUM DISORDER[1]

ABSTRACT

Studies comparing mathematical abilities of children with autism spectrum disorder (ASD) and typically developing children are hitherto scarce, inconclusive, and they mainly focus on elementary school children or adolescents. The current study wants to gain insight into the foundation of mathematics by looking at preschool performances. Five early numerical competencies known to be important for mathematical development were examined: verbal subitizing, counting, magnitude comparison, estimation, and arithmetic operations. These competencies were studied in 20 high-functioning children with ASD and 20 age-matched control children aged 4 and 5 years. Our data revealed similar early number processing in children with and without ASD at preschool age, meaning that both groups did not differ on the foundation of mathematics development. Given the pervasiveness and the family impact of the condition of ASD, this is an important positive message for parents and preschool teachers. Implications and several directions for future research are proposed.

[1] Based on Titeca, D., Roeyers, H. & Desoete, A. (revision submitted). Early numerical competencies in 4- and 5-year-old children with autism spectrum disorder. *Focus on Autism and Other Developmental Disabilities.*

INTRODUCTION

The interest in the academic functioning of children with *autism spectrum disorder* (*ASD*) has grown rapidly over the past few years. More and more children with ASD follow the regular educational program in mainstream educational settings, with or without additional guidance (Whitby & Mancil, 2009). Yet, given the high heterogeneity in ASDs, there is a wide variation in the level of functioning (Georgiades, Szatmari, & Boyle, 2013). As such, at least some children experience problems with their academic trajectory (Lanou, Hough, & Powell, 2012), and teachers are challenged to provide a comprehensive way of explaining certain subject matters (Kagohara, Sigafoos, Achmadi, O'Reilly, & Lancioni, 2012).

Mathematics seems to be one of the stumbling blocks for quite a large number of children with ASD, as there is a growing demand from clinical practice for adapted teaching methods on this subject (Department for Education and Skills, 2001; van Luit, Caspers, & Karelse, 2006). Three major cognitive theories dominate the psychological research into ASDs (Rajendran & Mitchell, 2007): the *theory of mind* (Baron-Cohen, Leslie, & Frith, 1985), the *theory of executive dysfunction* (Ozonoff, Pennington, & Rogers, 1991), and the *weak central coherence theory* (Frith, 1989). Previous research already demonstrated that the autism-specific cognitive profile may impact upon academic performance (Fleury et al., 2014; Jones, 2006; Pellicano, Maybery, Durkin, & Maley, 2006). Whether these cognitive theories can also be applied to explain in particular the mathematical profiles of children with ASD remains questionable, as research connecting these two topics hardly exists. One could for example assume an impact of theory of mind abilities on mathematical exercises involving perspective-taking, such as mathematical word problems. Moreover, because one of the aetiological cognitive factors supposedly contributing to *mathematical learning disorders* (*MLDs*) constitutes of deficits in executive functions (e.g., Andersson & Ostergren, 2012), one might also expect to observe mathematical problems in children with ASD. Finally, the weak central coherence theory can be linked to serial counting strategies (Gagnon, Mottron, Bherer, & Joanette, 2004; Jarrold & Russell, 1997), and to a discrepancy between preserved procedural and impaired conceptual skills in children with ASD (Goldstein, Minshew, & Siegel, 1994; Minshew, Goldstein, Taylor, & Siegel, 1994, Noens,

& van Berckelaer-Onnes, 2005). As such, autism-specific characteristics might impact, both negatively or positively, on mathematical functioning.

According to Mayes and Calhoun (2006), 23% of the children with autism have a MLD. Reitzel and Szatmari (2003) stated that 73% of the children with high-functioning autism (HFA) and 35% of the children with Asperger's Disorder (AD) have a general MLD, defined as a standard score < 80 on a mathematical achievement test. Moreover, 12% of the HFA group and 46% of the AD group had a specific MLD, defined as an IQ > 80 and minimum 15 points discrepancy with a math achievement test. These percentages are substantially higher than the prevalence estimates of MLD in the general school-aged population, which range from 2% to 14% (e.g., American Psychiatric Association [APA], 2013; Barbaresi, Katusic, Colligan, Weaver, & Jacobsen, 2005).

To date, studies comparing directly the mathematical abilities of children with ASD and typically developing (TD) children are scarce. The review of Chiang and Lin (2007) demonstrated average mathematical abilities in the majority of individuals with AD or HFA (aged 3 to 51 years) compared to the normed population. This was in line with previously reported average to good mathematical abilities of individuals with AD by Church, Alisanski, and Amanullah (2000). More recently, Iuculano et al. (2014) demonstrated even better numerical problem-solving abilities in elementary school children with HFA than in TD peers. None of these studies, however, provides a comprehensive overview of the mathematical abilities of children with ASD or focuses on the important developmental period of preschool age. Yet, several studies already demonstrated the importance of *early numerical competencies* as precursors for mathematical achievement later on, encouraged by the objective to prevent children from falling further behind by means of addressing early precursors as key components in remediation programs (DiPema, Lei, & Reid, 2007; Gersten et al., 2012; Jordan, Kaplan, Ramineni, & Locuniak, 2009).

Since practitioners often report mathematical difficulties in children with ASD from elementary school onward, it can be important to investigate early or preparatory competencies at a younger age. This would allow us to get insight into the possible precursors of the reported problems. If differences occur already at preschool level, this may suggest pre-existing difficulties with number processing leading to problems with mathematics later on.

Early numerical competencies

Children enter elementary school with varying levels of early number competencies (Jordan & Levine, 2009; Powell & Fuchs, 2012). Although it is clear that these early numerical competencies can be differentiated from the more complex mathematical abilities acquired through formal schooling, there is no consensus on the precise definition or even the term used to describe this set of abilities (Kroesbergen, van Luit, & Aunio, 2012). The current study included five early numerical competencies described in the work of Jordan and Levine (2009). All five competencies have proven to be important predictors of later mathematics achievement (Jordan & Levine, 2009).

Verbal subitizing. *Subitizing* is the rapid (40-100 ms/item) and accurate assessment of small quantities of up to three (or four) items (Kaufman, Lord, Reese, & Volkmann, 1949). Whereas children use counting to determine the exact numerosity of a large set of items, subitizing is considered to be a more automatic process for the precise representation of small numerosities (Dehaene, 1992; Nan, Knosche, & Luo, 2006). With increasing age, the reaction time slopes within the subitizing range become shallower, and the subitizing range itself expands (Basak & Verhaeghen, 2003; Svenson & Sjoberg, 1983).

Various studies have shown a relationship between subitizing abilities and later mathematics achievement (Desoete & Grégoire, 2006; Kroesbergen, van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; Reeve, Reynolds, Humberstone, & Butterworth, 2012). Moreover, subitizing is sometimes investigated as a core deficit in children with MLD (Fischer, Gebhardt, & Hartnegg, 2008; Schleifer & Landerl, 2011). Several studies suggested that children with ASD, due to a weaker central coherence (Frith & Happé, 1994), use a serial counting strategy rather than subitizing to enumerate small quantities (Gagnon et al., 2004; Jarrold & Russell, 1997). Nevertheless, no significant differences in reaction times or accuracy have been reported when comparing 15-year-old adolescents with ASD with TD peers (Gagnon et al., 2004) and children with and without ASD with a verbal mental age of 6.92 years (Jarrold & Russell, 1997). Regarding larger numerosities, it has been reported that some individuals with ASD show a process similar to that of subitizing to estimate these quantities (Snyder, Bahramali, Hawker, & Mitchell, 2006). However, this ability is considered as a savant skill that is only present in a very limited number of people with ASD (Snyder et al., 2006).

Counting. *Counting* knowledge can be subdivided into procedural (the ability to perform a counting task) and conceptual (the understanding of why a procedure works or is legitimate) aspects (LeFevre et al., 2006). Although closely related to each other, these two aspects seem to be mastered separately (Dowker, 2005). Previous studies indicated that children master the essential counting principles at age 4 to 5, but some children acquire these abilities only later on (Le Corre & Carey, 2007; Stock, Desoete, & Roeyers, 2009).

Since the 1980s, a large body of evidence has proven the central influence of counting on the development of adequate mathematical abilities and its supporting role in early mathematical strategies (Aunola, Leskinen, Lerkkanen, & Nurmi, 2004; Fuson, 1988; Le Corre, Van de Walle, Brannon, & Carey, 2006; Wynn, 1990). Moreover, children with MLD showed deficient counting abilities, indicating the importance of adequate and flexible counting knowledge (Dowker, 2005; Geary, Bowthomas, & Yao, 1992; LeFevre et al., 2006). As yet, there are no studies available on the counting abilities of individuals with ASD.

Magnitude comparison. *Magnitude comparison* is the ability to discriminate two quantities in order to point out the largest of both (Gersten et al., 2012), on the condition that the distance or ratio between the quantities is large enough (Halberda & Feigenson, 2008). The precision with which this can be done increases with age until young adulthood (Halberda & Feigenson, 2008).

Several studies demonstrated a relationship between the distance effect on a magnitude comparison task and later mathematics achievement (De Smedt, Verschaffel, & Ghesquiere, 2009; Holloway & Ansari, 2009) and the weaker performance of children with MLD on such tasks (Landerl, Bevan, & Butterworth, 2004; Mazzocco, Feigenson, & Halberda, 2011). To date, there is some evidence from a case study that some children with ASD might show superior magnitude comparison abilities (Soulieres et al., 2010).

Estimation. *Estimation*, often investigated with a number line task, is an important skill both in classroom and everyday life (Siegler & Opfer, 2003). Research indicates that the gain in precision of number line judgments is characterized by a developmental transition from a logarithmic representation to a more formally appropriate linear one, suggesting a changing representation with increasing formal schooling (Siegler & Booth, 2004; Siegler & Opfer, 2003).

The importance of this evolution is demonstrated in studies indicating that the linearity of judgments is positively correlated with math achievement scores (Ashcraft & Moore, 2012; Siegler & Booth, 2004). Moreover, compared to TD children, children with MLD are less accurate in their judgments and rely more on a logarithmic representation when dealing with this task (e.g., Geary, Hoard, Nugent, & Byrd-Craven, 2008). As yet, no studies have examined number line estimation in children with ASD.

Arithmetic operations. *Arithmetic operations* find themselves on the border between early numerical competencies and the more advanced mathematical knowledge acquired through formal teaching (Purpura & Lonigan, 2013). A first step to learn these simple addition and subtraction number combinations is often the use of manipulatives, followed by finger counting and eventually the use of reasoning strategies and memory-based retrieval (Groen & Resnick, 1977; Powell & Fuchs, 2012). Arithmetic operations can be measured through simple addition and subtraction exercises either with or without manipulatives, two-set addition, (de)composition of sets, and number combinations (Purpura & Lonigan, 2013). Many preschoolers have already an understanding of the numerical transformations involving addition and subtraction at 5 years of age (Huttenlocher, Jordan, & Levine, 1994).

Several studies demonstrated a relationship between arithmetic operations and later math achievement (Jordan, Glutting, & Ramineni, 2010; Jordan et al., 2009). Moreover, children with MLD perform worse on mathematical story problems than TD peers (Hanich, Jordan, Kaplan, & Dick, 2001; Jordan & Hanich, 2000). To date, there are no studies investigating arithmetic operations in children with ASD.

Objectives and research questions

Practitioners often report mathematical difficulties in children with ASD (Department for Education and Skills, 2001; van Luit et al., 2006). Moreover, as stated above, several autism-specific information processing characteristics could have an influence on mathematics performance. Hence, further research tackling this issue is warranted.

Whereas previous research often focused on one single aspect of mathematics (e.g., Gagnon et al., 2004) or used a composite math score (e.g., Chiang & Lin, 2007), the current study uses a multicomponential approach and incorporates different subcomponents of early mathematics. In addition, the current study puts a focus on the important developmental period of preschool age. As students who perform poorly on early numerical competencies tend to perform poor on mathematical achievement tests later on, early identification aimed at building interventions might be important (Dowker, 2005; Duncan et al., 2007).

The current study compared five early numerical competencies in TD children and high-functioning children with ASD at preschool age: verbal subitizing, counting, magnitude comparison, estimation, and arithmetic operations. The main goal was to investigate whether children with ASD differ in mathematics – encounter problems or show strengths in comparison with TD children – already before formal schooling (i.e., elementary school) starts. Moreover, the study wanted to identify for which of the early numerical competencies this is the case. Furthermore, the findings of this study were intended to direct future research. If preschool differences would be found (with children with ASD scoring lower than TD children), future research should focus on the underlying processes – such as autism-specific information processing characteristics – causing the differences in order to set up tailored interventions to prevent further problems. If no preschool differences would be found, this study might perhaps point to the fact that problems only arise from formal schooling onward, taking into account that practitioners have raised concerns on the mathematical abilities of elementary school children with ASD. Future research should try to confirm and map these statements. In case difficulties are witnessed, it would for example be useful to investigate if there is a need for evaluation or adaptation of the currently used teaching materials in order to optimize the mathematical learning of children with ASD.

The current study aimed to present an exploratory analysis of the early numerical competencies in 4- and 5-year-old children with and without ASD. Given the scarce and inconsistent results from previous studies, no specific hypotheses were postulated.

METHOD

Participants

Forty children (34 boys, 6 girls) with a mean age of 5.05 years (*SD* = 0.32) participated. In the Flemish part of Belgium, children typically attend preschool when they are aged 2.5 years, and enter elementary school at around age 6. Children usually attend preschool for 3 years. Although preschool education is not compulsory, the vast majority of children do attend preschool. Formal (with defined curriculum) and compulsory education starts in first grade. In the current study, all children had received two years of preschool education at the moment of testing. All children, although recruited from different schools, attended mainstream educational settings or special education specifically focused on high-functioning children with ASD. Within these two settings, the same *developmental goals* (i.e., a set of basic competencies that need to be acquired at the end of preschool) are set. As such, the children were assumed to receive similar preschool experiences concerning preparatory mathematics.

Children with ASD (17 boys, 3 girls) were recruited through rehabilitation centers, special school services, and other specialized agencies for developmental disorders. They had a formal diagnosis made independently by a qualified multidisciplinary team according to established criteria, such as specified in the *Diagnostic and Statistical Manual of Mental Disorders, 4th edition, Text Revision* (APA, 2000). For all children, this diagnosis was confirmed by a score above the ASD cut-off on the Dutch version of the *Social Responsiveness Scale* (*SRS*; Roeyers, Thys, Druart, De Schryver, & Schittekatte, 2011). The Dutch version of the *SRS* has a good internal consistency, with a Cronbach's alpha of .94 for boys and .92 for girls (Roeyers et al., 2011). Scores on the *Autism Diagnostic Observation Schedule* (*ADOS*; Lord et al., 2000) were available for 9 children with ASD. Children with and without *ADOS* scores did not differ significantly on the *SRS*, $U = 35.00$, $p = .295$. TD children (17 boys, 3 girls) were recruited using invitation letters sent to different preschool settings. There was no parental concern of developmental problems and all children scored below the ASD cut-off on the *SRS* (Roeyers et al., 2011).

Each participant had a full scale IQ (FSIQ) of 80 or more, measured with the *Wechsler Preschool and Primary Scale of Intelligence – Third edition* (*WPPSI-III*; Wechsler, 2002). As such, the study focused on a group of high-functioning children with

ASD. Due to the inclusion criteria of the *SRS* and the *WPPSI-III*, six children with ASD and two TD children were excluded from the study, resulting in 40 participants. Table 1 provides an overview of the sample characteristics. The two groups were matched on age, FSIQ, sex ratio, and socioeconomic status (*Hollingshead Four Factor Index of social status*; Hollingshead, 1975) on group level.

Table 1. *Descriptive characteristics of the sample*[2]

	TD (n = 20)		ASD (n = 20)			
	M	*(SD)*	*M*	*(SD)*	Test	
Age (in years)	4.98	(0.29)	5.13	(0.33)	$t(38) = -1.57$,	$p = .125$
FSIQ[a]	106.50	(11.61)	105.30	(13.90)	$t(38) = 0.30$,	$p = .769$
VIQ[b]	108.60	(13.76)	104.75	(12.26)	$t(38) = 0.93$,	$p = .356$
PIQ[c]	104.55	(7.98)	106.90	(17.78)	$t(26.35) = -0.54$,	$p = .593$
SES[d]	47.76	(9.66)	45.30	(9.47)	$U = 145.00$,	$p = .214$
SRS (*T*-score)[e]	46.90	(8.53)	86.25	(23.77)	$U = 19.00$,	$p < .001$

Note. Whenever the sampling distribution of the variables was not normally distributed, nonparametric analyses were conducted; TD = typically developing children, ASD = children with autism spectrum disorder; [a]Full Scale IQ, measured with *Wechsler Preschool and Primary Scale of Intelligence – Third edition*, [b]Verbal IQ, [c]Performance IQ, [d]Socioeconomic status, measured with the *Hollingshead index*, [e]*T*-score on *Social Responsiveness Scale*.

Materials

Verbal subitizing. All children were tested with a computerized enumeration task (see Praet, Titeca, Ceulemans, & Desoete, 2013 for further details), similar to the one described by Fischer et al. (2008) and based on the stimuli of Maloney, Risko, Ansari, and Fugelsang (2010). Participants saw one to nine black square boxes and were instructed to say aloud the number of squares as quickly and accurately as possible. The individual

[2] Despite the fact that nonparametric analyses were conducted in case of violations of the assumption of normality, we reported the parametric measures of central tendency and dispersion of the distribution, because these are more commonly reported in publications. This was done throughout all tables in this dissertation.

area, total area, and density of the squares were varied to insure that participants could not use non-numerical cues to make a correct decision (see Dehaene, Izard, & Piazza, 2005; Maloney et al., 2010). There were 15 practice trials and a test phase, which consisted of 72 samples (each numerosity was presented eight times) with a presentation time of 120 ms, a mask of 100 ms, and a total response time of 4,000 ms. This short presentation time prevented children from counting the squares (see Fischer et al., 2008). Both accuracy and mean reaction time (based on correct trials only) were used as outcome variables.

Counting. Counting was assessed using two subtests of the *Test for the Diagnosis of Mathematical Competencies* (*TEDI-MATH*; Grégoire, Noël, & Van Nieuwenhoven, 2004). The psychometric value of the battery was tested on a sample of 550 Dutch-speaking Belgian children (Grégoire, 2005). The *TEDI-MATH* has proven to be conceptually accurate and clinically relevant and its predictive value has been demonstrated in several studies (e.g., Desoete, Stock, Schepens, Baeyens, & Roeyers, 2009; Stock, Desoete, & Roeyers, 2007).

The procedural counting knowledge (subtest 1) was assessed using accuracy in counting row and counting forward to an upper bound and/or from a lower bound. The task had a maximum raw score of 8. The conceptual counting knowledge (subtest 2) was assessed by judging the validity of counting procedures based on the five basic counting principles formulated by Gelman and Galistel (1978). In order to investigate these principles, children had to count both linear and nonlinear patterns of objects, and were asked some questions about the counted amount of objects (e.g., “How many objects are there in total?”). Furthermore, they had to construct two numerically equivalent amounts of objects and use counting as a problem-solving strategy in a riddle. The maximum total raw score for this subtest was 13. The values for Cronbach’s alpha were .73 for procedural counting knowledge and .85 for conceptual counting knowledge.

Magnitude comparison. A computerized magnitude comparison task (see Praet et al., 2013 for further details) was used in line with Halberda and Feigenson (2008) and Inglis, Attridge, Batchelor, and Gilmore (2011). In this task, two displays of black dots were presented simultaneously and participants were instructed to press the sun- (leftmost) or the moon- (rightmost) button corresponding to the largest numerosity on a five-button response box as quickly and accurately as possible. Six different ratios were presented. When dividing the smallest by the largest numerosity, these ratios were: .33, .50, .67, .75, .80, and .83. The individual area, total area, and density of the squares were varied to insure that participants could not use non-numerical cues to make a decision (see Dehaene et al., 2005). There were 15 practice trials and a test phase, which consisted of 72 samples (each ratio was presented twelve times) with a presentation time of 1,200 ms, a mask of 2,800 ms, and a total response time of 4,000 ms. Accuracy and mean reaction time (based on correct trials only) were used as outcome variables.

Estimation. A number line estimation task with a 0-10 interval was used, based on the procedure of Siegler and Opfer (2003) and the task of Berteletti, Lucangeli, Piazza, Dehaene, and Zorzi (2010). The task included 3 practice trials and 27 test trials. Stimuli were presented in a visual Arabic format (e.g., anchors 0 and 10, target number 3), an auditory-verbal format (e.g., anchors zero and ten, target number three), and an analog magnitude format (e.g., anchors of zero dots and ten dots, target number three dots). The dot patterns consisted of black dots in a white disc controlled for perceptual variables using the procedure of Dehaene et al. (2005). During test trials, all numbers of the interval except for 0 and 10 had to be positioned on the line, for all three formats. Children were asked to put a single mark on the line to indicate the location of the number. Although the instructions could be rephrased if needed, no feedback was given to participants regarding the accuracy of their marks. The percentage of absolute error (PAE) was calculated per child as a measure of children's estimation accuracy, following the formula of Siegler and Booth (2004).

To investigate the underlying representation of the estimates, the procedure of Siegler and Opfer (2003) was used. On group level, regression analyses on the group medians were conducted to compute both linear and logarithmic fits. The difference between the two fits was tested with a paired samples t-test, conducted on the calculated absolute difference between the median estimate for each number and the predicted values based on the linear and logarithmic model respectively. On individual level, following the procedure of Berteletti et al. (2010), each child was attributed the best fitting significant model between linear and logarithmic. A child was classified as not having a valid representation when both coefficients failed to reach significance or when slopes were negative.

Arithmetic operations. Arithmetic operations were assessed using subtest 5.1 of the *TEDI-MATH* (Grégoire et al., 2004). A series of six visually supported addition and subtraction exercises was presented to the children (e.g., "Here you can see two red balloons and three blue balloons. How many balloons are there altogether?"). The maximum total raw score was 6. Cronbach's alpha of this subscale was .85.

Procedure

The study was approved by the ethical commission of the Faculty of Psychology and Educational Sciences of Ghent University. Parents received an information letter and signed an informed consent before their participation. Children were assessed individually, but the tests were presented in the same order for all children. It took approximately two hours for participants to complete the test battery. The assessment was spread over two different test sessions. In the first session, children were assessed with the *WPPSI-III* (Wechsler, 2002) and with the computerized tasks (verbal subitizing and magnitude comparison). During the second session, children were assessed with the *TEDI-MATH* tasks (counting and arithmetic operations) and the number line task (estimation). All test leaders (graduate students) received training in the assessment and interpretation of the tests.

RESULTS

In order to check whether the sampling distribution of the variables was normally distributed within groups, a Shapiro-Wilk test (for sample sizes lower than 50; Field, 2009) was used. Parametric analyses were conducted, except for the cases in which the assumption for normal distributions was violated ($p < .050$). Table 2 provides an overview of the correlations between all variables. Significantly different correlation patterns seemed to emerge for TD children and children with ASD for some of the variables (Fisher r-to-z transformations, $p < .050$). However, only few significant correlations were found between the constructs, and after applying a Bonferroni correction ($p < .001$) none of the correlations remained significant.

Table 2. *Correlations between early numerical competencies, full scale IQ, and severity of ASD symptomatology*

		VS[a]		C[d]		MC[g]		E[h]	AO[j]	FSIQ[k]
		RT[b] (1-3)	ACC[c] (1-3)	PC[e]	CC[f]	Overall RT[b]	Overall ACC[c]	Overall PAE[i]		
VS[a]										
RT[b] (1-3)	**TD**	**-**								
	ASD	-								
ACC[c](1-3)	**TD**	**.45**	**-**							
	ASD	-.63*	-							
C[d]										
PC[e]	**TD**	**-.23**	**.02**	**-**						
	ASD	-.49^{t}	.49^{t}	-						
CC[f]	**TD**	**-.12**	**.18**	**.62****	**-**					
	ASD	-.66**	.58*	.61**	-					
MC[g]										
Overall RT[b]	**TD**	**-.56***	**-.25**	**.10**	**.06**	**-**				
	ASD	-.09	-.30	.30	.20	-				
Overall ACC[c]	**TD**	**-.08**	**-.15**	**.11**	**.39**	**.17**	**-**			
	ASD	-.06	.29	.52*	.13	.04	-			
E[h]										
Overall PAE[i]	**TD**	**.11**	**.16**	**-.14**	**-.14**	**-.62****	**-.12**	**-**		
	ASD	.29	-.34	-.20	-.36	.11	.17	-		
AO[j]	**TD**	**-.67****	**-.33**	**.50***	**.36**	**.34**	**-.01**	**-.14**	**-**	
	ASD	-.23	.27	.62**	.49*	.08	.14	-.21	-	
FSIQ[k]	**TD**	**-.01**	**-.41**	**.30**	**.11**	**.04**	**.22**	**-.24**	**.39^{t}**	**-**
	ASD	.24	-.23	.13	.10	.17	.19	-.23	.44^{t}	-
SRS[l]	**TD**	**-.17**	**.09**	**-.37**	**-.02**	**.08**	**.12**	**-.15**	**.15**	**-.13**
	ASD	.10	-.02	.20	.24	-.11	-.05	.23	.38	-.30

Note. $^{t}p < .100$, $^{*}p < .050$, $^{**}p < .010$; underlined correlations indicate a significantly stronger (absolute value) correlation than in the other group (Fisher r-to-z transformation, $p < .050$); TD = typically developing children, ASD = children with autism spectrum disorder; [a]Verbal subitizing, [b]Reaction time, [c]Accuracy, [d]Counting, [e]Procedural counting, [f]Conceptual counting, [g]Magnitude comparison, [h]Estimation, [i]Percentage of absolute error, [j]Arithmetic operations, [k]Full scale IQ, [l]Raw score on *Social Responsiveness Scale.*

Verbal subitizing

Due to technical reasons (recording problems), the results of six TD children and four children with ASD were not recorded. In addition, one child with ASD was excluded, as the child did not understand the task properly and could not complete it. Therefore, analyses were conducted on 14 TD children and 15 children with ASD.

Graphical inspection of the accuracy rates revealed very low accuracy scores for larger numerosities (> 5). As such, only numerosities 1 to 5 were included in the reaction time analyses. This range of numerosities was chosen because 5 was the highest numerosity at which reaction time data were present for more than half of the children of whom data were available (n = 19).

A Friedman ANOVA demonstrated a significant main effect of numerosity in both groups, $\chi^2(4) = 16.44$, $p = .002$ in the TD group (n = 9) and $\chi^2(4) = 16.96$, $p = .002$ in the ASD group (n = 10), with higher reaction times for increasing numerosities (see Figure 1). A Mann-Whitney U test revealed no significant difference in mean reaction time for the range 1-5 between the two groups, $U = 102.00$, $p = .914$. When focussing specifically on the subitizing range (1-3), there was also no significant difference between the two groups, $U = 84.00$, $p = .377$.

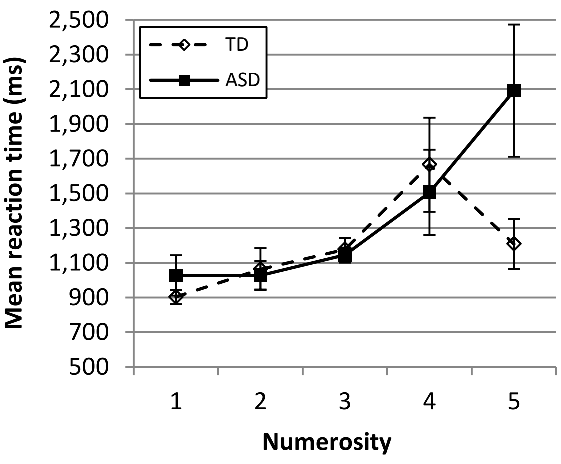

Figure 1. Verbal subitizing – Reaction time in function of numerosity.
Note. TD = typically developing children; ASD = children with autism spectrum disorder.

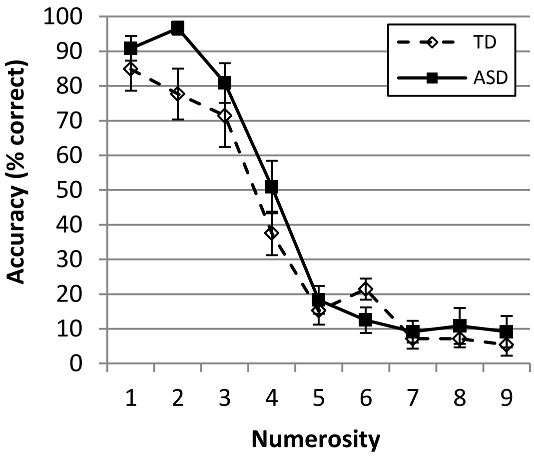

Figure 2. Verbal subitizing – Accuracy in function of numerosity.
Note. TD = typically developing children; ASD = children with autism spectrum disorder.

For accuracy, a Friedman ANOVA on all numerosities revealed a significant main effect of numerosity in both groups, $\chi^2(8) = 79.86$, $p < .001$ in the TD group ($n = 14$) and $\chi^2(8) = 94.67$, $p < .001$ in the ASD group ($n = 15$), with lower accuracy rates for increasing numerosities (see Figure 2). No significant differences in total accuracy, $U = 69.50$, $p = .123$, or accuracy in the subitizing range (1-3), $U = 68.00$, $p = .112$, were found between the groups.

Counting

An independent samples t-test revealed no significant difference neither in procedural counting knowledge, $t(38) = -0.43$, $p = .673$, nor in conceptual counting knowledge, $t(38) = 0.12$, $p = .903$, between children with ASD and TD children (see Figure 3).

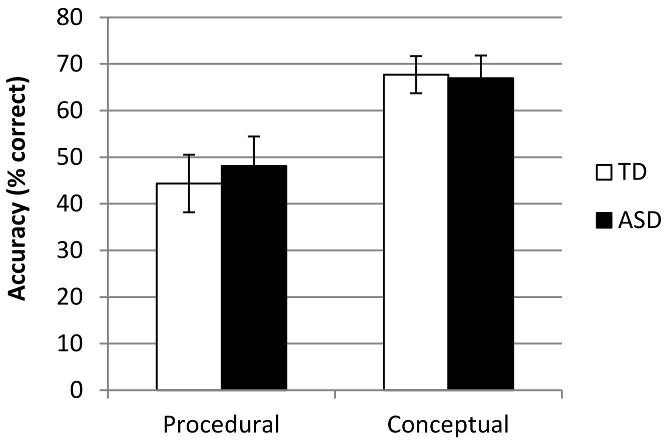

Figure 3. Counting – Accuracy for procedural and conceptual counting knowledge. *Note.* TD = typically developing children; ASD = children with autism spectrum disorder.

Magnitude comparison

Due to technical reasons (recording problems), the results of six TD children and four children with ASD were not recorded. Analyses were conducted on 14 TD children and 16 children with ASD.

A repeated measures analysis on mean reaction time with ratio as within-subject factor and group as between-subject factor revealed no significant main effect of ratio, $F(5, 24) = 1.85$, $p = .140$, or group, $F(1, 28) = 0.12$, $p = .728$. Moreover, there was no significant ratio × group interaction, $F(5, 24) = 0.10$, $p = .990$ (see Figure 4).

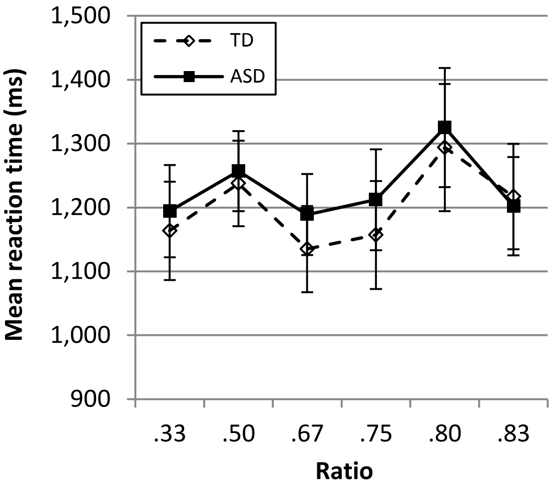

Figure 4. Magnitude comparison – Reaction time in function of ratio.
Note. TD = typically developing children; ASD = children with autism spectrum disorder.

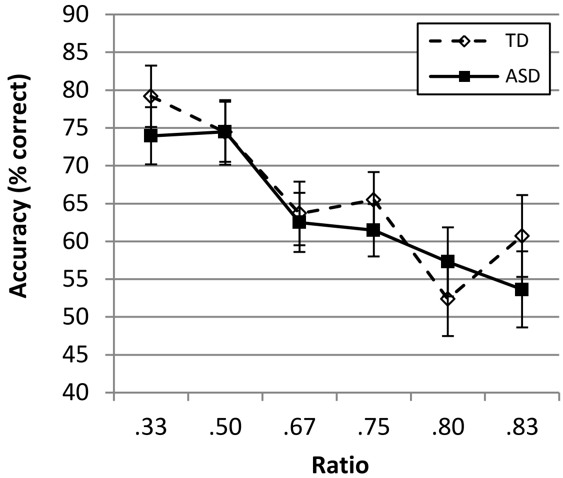

Figure 5. Magnitude comparison – Accuracy in function of ratio.
Note. TD = typically developing children; ASD = children with autism spectrum disorder.

For accuracy, a repeated measures analysis revealed a significant main effect of ratio, $F(5, 24) = 16.78$, $p < .001$. However, there was no significant main effect of group, $F(1, 28) = 0.26$, $p = .614$, and no ratio × group interaction, $F(5, 24) = 0.70$, $p = .632$ (see Figure 5).

Estimation

Three TD children and three children with ASD were excluded from the analyses, as they did not understand the task properly (i.e., positioning all estimates in the middle or positioning all estimates at one anchor).

A Friedman ANOVA demonstrated no significant differences in PAE between the three presentation formats, $\chi^2(2) = 2.47$, $p = .291$ in the TD group and $\chi^2(2) = 1.41$, $p = .494$ in the ASD group. A Mann-Whitney U test indicated no significant difference between the groups for the total PAE, $U = 104.00$, $p = .110$ (see Figure 6).

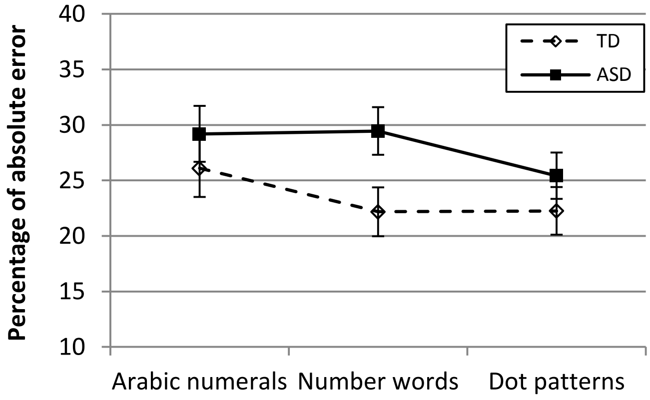

Figure 6. Estimation – Percentages of absolute error in function of format. *Note.* TD = typically developing children; ASD = children with autism spectrum disorder.

When investigating the shape of the curve, the underlying representation was examined both at group and individual level. On group level, the best fitting representational model for the overall number line task was linear for both the TD group, R^2_{lin} = .91, p < .001, and the ASD group, R^2_{lin} = .96, p < .001. However, this linear fit was not significantly different from the logarithmic model in both the TD group, R^2_{log} = .86, p < .001; t(8) = -1.01, p = .342, and the ASD group, R^2_{log} = .90, p < .001; t(8) = -2.16, p = .063. The shape of the curve is illustrated in Figure 7 and Figure 8 for the TD group and ASD group respectively.

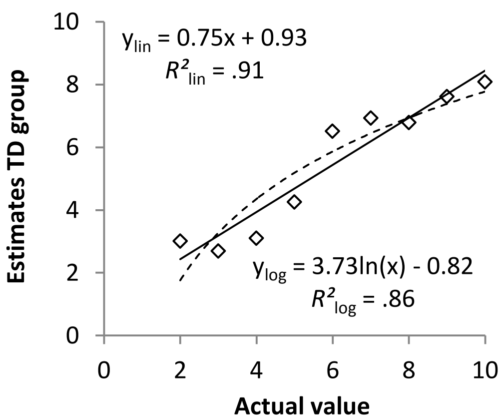

Figure 7. Estimation – Linear and logarithmic fit of typically developing (TD) children.

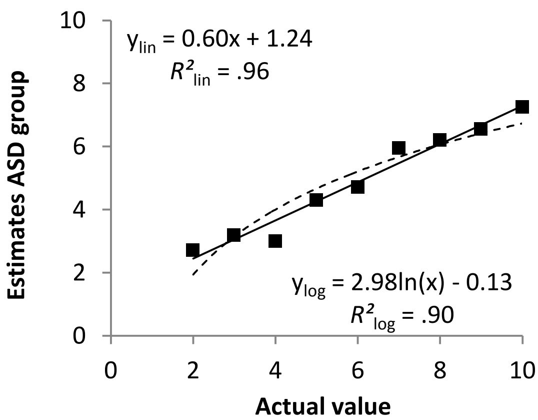

Figure 8. Estimation – Linear and logarithmic fit of children with autism spectrum disorder (ASD).

At the individual level, no significant differences between both groups, Fisher exact test, p = .122, were found between the allocation to the following categories: no valid representation (TD: 23.53%; ASD: 52.94%) – logarithmic representation (TD: 41.18%; ASD: 11.76%) – linear representation (TD: 35.29%; ASD: 35.29%).

Arithmetic operations

A Mann-Whitney U test revealed no significant difference in the ability to execute arithmetic operations between TD children and children with ASD, U = 184.50, p = .678 (see Figure 9).

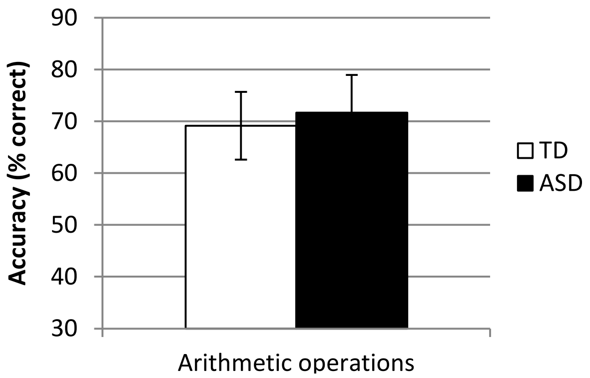

Figure 9. Arithmetic operations – Accuracy rates.
Note. TD = typically developing children;
ASD = children with autism spectrum disorder.

DISCUSSION

This study aimed at comparing the five early numerical competencies as outlined in the review of Jordan and Levine (2009) between 4- and 5-year-old children with and without ASD, attending the second year of preschool. Despite the clinical concerns and the theoretical arguments to assume an influence of some autism-specific information processing characteristics on mathematical abilities, research on mathematics in children with ASD is rather scarce and is just starting to become a topic of interest. Therefore, the goal of this study was to provide an exploratory analysis of possible differences in mathematical abilities at preschool age – a necessary first step before deciding whether investigating underlying processes is useful.

Overall, the current study found similar early number processing in children with and without ASD at the age of 4 or 5 years. This finding is consistent with some of the previous studies that targeted mathematical abilities of children with ASD at a later age, and found average mathematical abilities compared to the normed population (Chiang & Lin, 2007; Church et al., 2000; Iuculano et al., 2014). Moreover, no significant correlations were found between ASD symptomatology and early numerical competencies. The fact that the foundation of mathematical development in high-functioning children with ASD is similar to that of TD children is an important finding. Given the pervasiveness of the condition of ASD on other domains of functioning (Jones, 2006), it is encouraging to know that, at first blush, no additional concerns should be raised on the early numerical competencies.

Next to these general findings, some results will be discussed and related to previous findings in more detail below. Regarding *verbal subitizing*, our results are in line with previous findings that demonstrated no significant differences in reaction times or accuracy rates in older children (Jarrold & Russell, 1997) or adolescents (Gagnon et al., 2004) with ASD. Moreover, we found no indications of a process similar to subitizing for larger numerosities (Snyder et al., 2006) in preschoolers with ASD, as reflected by the increase in reaction time and the large decrease of accuracy for larger numerosities. Our task was specifically designed to assess subitizing (giving the participants not enough time to count all items) and therefore it is clear that our participants (with or without ASD) did not succeed in subitizing/quickly estimating larger numerosities. For *magnitude comparison*, our results expounded on the case study of Soulieres et al. (2010) and revealed no significant differences between children with ASD and TD children. Given the large behavioral heterogeneity in children with ASD (Georgiades et al., 2013), it remains possible that some children show superior performance on for example magnitude comparison. However, our results revealed that this superior performance does not hold when examining children with ASD at group level. Finally, despite the fact that the *estimation* task was operationalized in a different way compared to previous studies (three formats instead of Arabic numerals only), the PAEs (24% for TD children and 28% for children with ASD) were similar to a previous report for the same 0-10 interval at the same age (24% in Berteletti et al., 2010). Although previous research indicated divergent findings regarding mathematical functioning depending on the format (symbolic versus nonsymbolic) that is used (De Smedt, Noël, Gilmore, & Ansari, 2013), the added value of incorporating different presentation formats could not be demonstrated in the current study.

Strengths and limitations

Since previous studies on mathematical abilities in children with ASD are scarce and investigate mostly older children or adolescents, the current study provides valuable insights into the important developmental period of preschool age, in which the first mathematical milestones have to be reached. Indeed, early numerical competencies are predictive for later mathematics in TD children (Jordan & Levine, 2009). As such, studying these precursors can also be informative in children with ASD. However, it is recommended that future research adopts a longitudinal approach to confirm these findings and to indicate their predictive value in children with ASD.

In addition, whereas previous research often focused on one single aspect of mathematics (e.g., Gagnon et al., 2004) or used a composite math score (e.g., Chiang & Lin, 2007), the current study used a multicomponential approach and incorporated the different early numerical competencies described by Jordan and Levine (2009). In this way, the study provided the possibility to reflect a differentiated profile of strengths, average scores, or weaknesses compared to TD children (if such divergent scores on early numerical competencies would be present). Moreover, the use of a matched control group instead of the normed samples of standardized achievement tests makes a more reliable and direct comparison on all competencies possible.

Caution is however needed when interpreting the results, as only a small number of children was included in the sample. Obviously, sample size is not a problem for significant differences, but when analyses have insufficient power and are not significant, a risk of type 2- or β-mistakes cannot be excluded (Field, 2009). The number line estimation data, for example, showed a somewhat higher accuracy for TD children compared to children with ASD (see Figure 6) and quite large differences in allocations to representation categories; differences that might turn significant in larger samples. Additional research with a larger group of participants is therefore indicated. Moreover, the current study only included high-functioning children with ASD, so additional studies on children with ASD with lower intellectual levels are recommended.

In addition, given the typical heterogeneity in academic profiles of children with ASD (e.g., Estes, Rivera, Bryan, Cali, & Dawson, 2011; Georgiades et al., 2013), it might also be interesting to look for possible subgroups of children. Looking at average scores may mask subgroups of individuals with remarkable poor or excellent skills (Jones et al., 2009). As such, future research with larger groups of children could consider to conduct cluster analyses to identify possible subgroups.

Finally, it is important to note that although the instruments are previously used in TD populations or children with MLD (e.g., Berteletti et al., 2010; Praet et al., 2013; Stock et al., 2007), most of the instruments have never been used in an ASD group before. In addition, the wide range of test trials of the different early numerical competencies can be considered as a limitation that may have influenced the results.

Implications

The current study indicated a similar performance in early numerical competencies between children with ASD and TD children at the ages of 4 and 5 years. Given the pervasiveness and the family impact of the condition of ASD (Karst & Van Hecke, 2012), this message can considered to be valuable to communicate to parents and teachers. Acknowledging strengths or abilities is important, not only to compensate for weaknesses, but also for increasing self-esteem and well-being (Jones, 2006). Given our findings, it can be assumed that the early foundation of mathematical development in high-functioning children with ASD is rather similar to that of TD children, meaning that the instructional approaches of early numerical competencies used by teachers or parents should not be adapted for high-functioning children with ASD. However, this recommendation should be treated carefully, given the small and selective sample of the current study.

Either way, given the concerns on mathematics in elementary school children with ASD formulated by clinicians and practitioners, it is still warranted to follow up the mathematical abilities at later ages, because the transition to formal schooling could have an impact (either positive or negative) on mathematics performance.

Conclusion

The current study indicates a similar performance on early numerical competencies in children with ASD and TD children at 4 and 5 years of age, suggesting a typical early number processing in preschool in children with ASD. Future research is indicated to investigate whether or not differences in mathematics performance between TD children and children with ASD arise gradually during schooling.

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CHAPTER 3

EARLY NUMERICAL COMPETENCIES IN 5- AND 6-YEAR-OLD CHILDREN WITH AUTISM SPECTRUM DISORDER[1]

ABSTRACT

To date, studies comparing the mathematical abilities of children with autism spectrum disorder (ASD) and typically developing children are scarce, and results remain inconclusive. In general, studies on this topic focus on mathematical abilities learned from elementary school onward, with little attention for possible precursors at younger ages. The current study focused on the important developmental period of preschool age, investigating five early numerical competencies in 30 high-functioning children with ASD and 30 age-matched control children: verbal subitizing, counting, magnitude comparison, estimation, and arithmetic operations. Children were examined at 5 or 6 years of age, attending the third and final year of preschool. Overall, rather similar early number processing in children with and without ASD was found, although marginally significant results indicated a weaker performance of children with ASD on verbal subitizing and conceptual counting. Given the pervasiveness and impact of ASD on other domains of functioning, it is important to know that no general deficits in early numerical competencies were found. However, some downward trends in mathematics performance were identified in children with ASD, which can serve as basis for additional research in this ground.

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INTRODUCTION

The ability to recognize and diagnose high-functioning children with *autism spectrum disorder* (*ASD*) has improved over the last years (Adreon & Durocher, 2007). Likewise, more and more of these children are included in mainstream educational settings and make the transition to college, trying to obtain meaningful employment (Adreon & Durocher, 2007). Despite being high-functioning, these children seem to struggle in general educational settings, having difficulties to reach their full potential (C.R.G. Jones et al., 2009; Whitby & Mancil, 2009). At present, there is a growing suggestion in clinical practice that mathematics is one of the stumbling blocks for quite a large number of children with ASD (Department for Education and Skills, 2001; van Luit, Caspers, & Karelse, 2006).

Early numerical competencies

Children enter elementary school with varying levels of early number competencies (N. C. Jordan & Levine, 2009; Kroesbergen, van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; Passolunghi & Lanfranchi, 2012; Powell & Fuchs, 2012). Since several studies have lent support for the predictive value of those *early numerical competencies* for later mathematics, preschool seems to impose an important developmental period to focus on when conducting mathematics research. Previous studies have identified several key precursors of later mathematics performance, which have been summarized into one framework by N. C. Jordan and Levine (2009). Each component of this framework, along with its significance for later mathematics performance, will be discussed in detail below.

Verbal subitizing is the ability to rapidly and accurately enumerate small quantities of up to three (or four) items (Kaufman, Lord, Reese, & Volkmann, 1949). Various studies demonstrated that subitizing is an important factor in mathematical development (Landerl, Bevan, & Butterworth, 2004; Penner-Wilger et al., 2007; Träff, 2013), and longitudinal research showed that subitizing is a domain-specific predictor for later mathematical performance over and above domain-general abilities (Gray & Reeve, 2014; Krajewski & Schneider, 2009; LeFevre et al., 2010; Reigosa-Crespo et al., 2012). *Counting* includes both the procedural knowledge to execute a counting task and the conceptual knowledge to understand the counting principles (LeFevre et al., 2006). Whereas procedural counting knowledge is predictive for numerical facility, conceptual counting knowledge is predictive for untimed mathematical achievement (Desoete, Stock, Schepens, Baeyens, & Roeyers, 2009). Counting as a whole, in its turn, influences the development of adequate mathematical abilities and supports early mathematical strategies (Aunola, Leskinen, Lerkkanen, & Nurmi, 2004; Fuson, 1988; Le Corre, Van de Walle, Brannon, & Carey, 2006; Wynn, 1990). *Magnitude comparison* involves the ability to discriminate two quantities in order to point out the largest of both (Gersten et al., 2012). Number comparison, both symbolic (Bartelet, Vaessen, Blomert, & Ansari, 2014; Holloway & Ansari, 2009; Sasanguie, De Smedt, Defever, & Reynvoet, 2012; Sasanguie, Gobel, Moll, Smets, & Reynvoet, 2013) and nonsymbolic (Halberda, Mazzocco, & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2013; Mazzocco, Feigenson, & Halberda, 2011), has proven to play an important role in the development of mathematical abilities (De Smedt, Verschaffel, & Ghesquiere, 2009). *Estimation* refers to the ability to estimate the position of a given number on a number line (Siegler & Opfer, 2003). Several studies support the importance of number-space mapping for mathematical ability: Both the linearity of number line judgments (Ashcraft & Moore, 2012; Siegler & Booth, 2004) and the estimation accuracy (Sasanguie et al., 2012; Sasanguie et al., 2013) have proven to be correlated with math achievement scores. Finally, *arithmetic operations* assess the ability to solve simple addition and subtraction exercises (Purpura, Hume, Sims, & Lonigan, 2011). Arithmetic operations, as part of a larger early numerical competencies battery, have proven to be predictive for later mathematical abilities, especially for applied problem solving (N. C. Jordan, Glutting, & Ramineni, 2010; N. C. Jordan, Kaplan, Ramineni, & Locuniak, 2009).

Early numerical competencies have been related not only to typical but also to atypical mathematical development. Several studies demonstrated that children with a *mathematical learning disorder* (*MLD*) show impairments in subitizing (Fischer, Gebhardt, & Hartnegg, 2008; Schleifer & Landerl, 2011), counting (Dowker, 2005; LeFevre et al., 2006), magnitude comparison (Landerl et al., 2004; Piazza et al., 2010), estimation (Geary, Hoard, Nugent, & Byrd-Craven, 2008; Landerl, 2013), and arithmetic operations (Hanich, Jordan, Kaplan, & Dick, 2001; N. C. Jordan & Hanich, 2000).

Mathematical abilities in children with autism spectrum disorder

Although practitioners express concerns on the mathematical abilities of children with ASD (Department for Education and Skills, 2001; van Luit et al., 2006), several anecdotal and descriptive reports provide contrasting evidence of mathematics proficiency in individuals with ASD (Baron-Cohen, Wheelwright, Burtenshaw, & Hobson, 2007; Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001; Sacks, 1986; Smith 1983). In addition, from a theoretical perspective, divergent predictions on how children with ASD will perform on mathematics can be made. Three major cognitive theories dominate the psychological research into ASDs (Rajendran & Mitchell, 2007). Previous research already demonstrated that the autism-specific cognitive profile may impact upon academic performance (Fleury et al., 2014). Whether these cognitive theories can also be applied to explain in particular the mathematical profiles of children with ASD remains questionable, as research connecting these two topics hardly exists. The *theory of mind hypothesis* (Baron-Cohen, Leslie, & Frith, 1985) postulates that individuals with ASD have difficulties with attributing mental states to self and others in order to understand and predict behavior. Given its strong involvement in social-communicative deficits, it seems unlikely to deduce large consequences for the domain of mathematics. However, one could assume an impact of theory of mind abilities on mathematical exercises involving perspective-taking, such as mathematical word problems. On the one hand, one could assume less deceit for mathematical word problems because of a smaller urgency to read the speaker's mind (Frith & Happé, 1996). On the other hand, one could assume a weaker performance in exercises urging a correct use of mental state terms. The *theory of executive dysfunction* (Ozonoff, Pennington, & Rogers, 1991) postulates, as opposed to the theory of mind hypothesis, a domain-general cognitive deficit. Because one of the aetiological cognitive factors supposedly contributing to MLD constitutes of deficits in executive functions (e.g., Andersson & Ostergren, 2012; Geary, Hoard, Nugent, & Bailey, 2012), one might also expect to observe mathematical problems in children with ASD. Impairments in working memory have proven to play a role in number fact retrieval deficits (Geary, 1993; Geary, Hoard, Byrd-Craven, & DeSoto, 2004) and delayed procedural development (Geary, 1993, 2004). Although results are sometimes contradictory (Kolkman, Hoijtink, Kroesbergen, & Leseman, 2013), it has also been argued that problems with inhibition (Bull & Scerif, 2001), shifting (Kroesbergen et al., 2009), and naming speed/fluency (Geary, 2011; Temple & Sherwood, 2002) are linked to mathematical abilities and disorders. Finally, according to the *weak central coherence theory* (Frith, 1989), individuals with ASD are hypothesized to have a cognitive style characterized by a processing bias for featural and local information, and a relative failure to extract global information (Frith & Happé, 1994). Regarding the field of mathematics, the weak central coherence theory has been linked to verbal subitizing in children with ASD. Several studies suggested that children with ASD – due to a weaker central coherence – use a serial counting strategy rather than a subitizing process to enumerate small quantities (Gagnon, Mottron, Bherer, & Joanette, 2004; Jarrold & Russell, 1997). Moreover, it has been argued that children with ASD would show preserved procedural and mechanical skills, but impaired complex information processing abilities (Goldstein, Minshew, & Siegel, 1994; Minshew, Goldstein, Taylor, & Siegel, 1994), which has later been linked to the weak central coherence framework (Noens & van Berckelaer-Onnes, 2005). However, these findings adhered mainly to literacy and have not yet been demonstrated for the field of mathematics (Goldstein et al., 1994; Minshew et al., 1994). We can conclude that, when considering these theoretical accounts, the autism-specific information processing characteristics might exert both a negative or positive impact upon academic or mathematical functioning (G. Jones, 2006; Pellicano, Maybery, Durkin, & Maley, 2006). These inconclusive and uninvestigated hypotheses highlight the need for empirical research on this topic.

To date, such research investigating mathematical abilities of children with ASD is not only scarce, but also leaves us with indecisive results. First, some studies suggest a weakness for mathematics in children with ASD. Comorbidity studies, for example, demonstrated higher comorbidity rates of MLD and ASD in children aged 6-16 years (Mayes & Calhoun, 2006; Reitzel & Szatmari, 2003) compared to the prevalence rate of MLD in the general population (e.g., Barbaresi, Katusic, Colligan, Weaver, & Jacobsen, 2005). Moreover, some studies comparing mathematics performance to general intellectual functioning suggested a relatively low score on mathematics compared to general functioning. Chiang and Lin (2007), for example, conducted a review based on 18 articles, covering an age range of 3-51 years. They reported a relative weakness in mathematics in individuals with ASD. Mayes and Calhoun (2003) investigated school-aged children (6-15 years) with ASD and reported that 22% of the high-functioning children with ASD had a MLD. A second group of studies suggest however that mathematics is a strength in individuals with ASD. C.R.G. Jones et al. (2009), for example, indicated that 16.2% of the adolescents (14-16 years) with ASD show a relative strength in mathematics whereas only 6.1% of them demonstrated a relative weakness. Moreover, Mayes and Calhoun (2003) found that the score on Quantitative Reasoning exceeded other factor or area scores of the *Stanford-Binet:IV* in children aged 3-7 years. However, no significant differences in *Stanford-Binet:IV* IQ and math scores on a standardized achievement test could be found (Mayes & Calhoun, 2003). Furthermore, Iuculano et al. (2014) demonstrated that children with ASD aged 7-12 years have superior numerical problem-solving abilities compared to typically developing (TD) peers. This finding was in line with the average to above-average mathematical abilities, compared to TD children, reported in the descriptive study of Church, Alisanski, and Amanullah (2000). In addition, Soulieres et al. (2010) conducted a case study on special abilities and reported that certain individuals with ASD (9 years of age) may indeed develop superior and specialized abilities in estimation, in this case operationalized with a magnitude comparison task. Finally, some studies argue for average or similar mathematical abilities in children with ASD when compared to the normed population or TD peers. Chiang and Lin (2007), for example, reported this finding in their review comparing children with ASD to the normed population. Iuculano et al. (2014) also reported average abilities on mathematical reasoning (word and language based problems) compared to TD peers. In addition, some studies investigating verbal subitizing reported no differences in accuracy or reaction times between children with ASD and TD children, aged 10-21 years (Gagnon et al., 2004) and 6-12 years (Jarrold & Russell, 1997). As such, the former research on mathematical abilities of children with ASD reveals inconsistent findings.

One explanation for these inconsistencies might be the large heterogeneity observed in children with ASD (Georgiades, Szatmari, & Boyle, 2013). Another explanation stems from the fact that different approaches and research questions are handled within the different studies, with some studies focusing on within-group differences (mathematical abilities relative to own cognitive abilities; e.g., C.R.G. Jones et al., 2009; Mayes & Calhoun, 2003) and others on between-group differences (mathematical abilities of children with ASD compared with TD children; e.g., Gagnon et al., 2004; Iuculano et al., 2014).

Objectives and research questions

In the current study, a between-group approach was applied in which the mathematical abilities of children with ASD were compared to those of TD children. In doing so, we aimed to add to the existing literature by addressing some limitations of previous research. First, none of the aforementioned studies applying a between-group perspective focused on the important developmental period of preschool age. Although verbal subitizing (Gagnon et al., 2004; Jarrold & Russell, 1997) and magnitude comparison (Soulieres et al., 2010) have been studied in elementary school children with ASD, information on early numerical competencies at preschool age is nonexisting. In TD children, early numerical competencies in preschool are predictive for later mathematics in elementary school (N. C. Jordan & Levine, 2009; Kroesbergen, van Luit, & Aunio, 2012; Navarro et al., 2012; Passolunghi & Lanfranchi, 2012). Moreover, in our previous study (Titeca, Roeyers, Josephy, Ceulemans, & Desoete, 2014), we addressed the predictive value of early numerical competencies for first grade mathematics in children with ASD. Results indicated that counting and especially verbal subitizing were important predictors of first grade mathematics in children with ASD (Titeca et al., 2014). As such, studying the precursors that serve as a foundation for later mathematics performance could be informative. Second, recent studies in the field of mathematics emphasize the importance of incorporating a multicomponential approach instead of applying one math composite score (J. A. Jordan, Mulhern, & Wylie, 2009; Mazzocco, 2009; Simms, Cragg, Gilmore, Marlow, & Johnson, 2013). Therefore, multiple early numerical competencies were investigated in the current study.

The current study examined five early numerical competencies in high-functioning children with ASD and TD children at 5 and 6 years of age. The main goal was to provide an exploratory analysis, investigating whether children with ASD differ from TD children on verbal subitizing, counting, magnitude comparison, estimation, and arithmetic operations. Based on the cognitive theories of autism, different hypotheses might be formulated. In line with the weak central coherence account, one might expect to find weaknesses on tasks with nonsymbolic stimuli (i.e., verbal subitizing, magnitude comparison, and estimation of dot patterns) and conceptual knowledge (i.e., conceptual counting), but intact procedural skills (i.e., procedural counting and arithmetic operations). However, based on the executive dysfunction theory, impairments in procedural skills could be assumed. Since no word problems involving mental states were included, we did not assume any influence from the theory of mind account. Based on empirical research using a between-group perspective in older children, children with ASD were expected to score average or better compared to TD children (e.g., Chiang & Lin, 2007; Gagnon et al., 2004; Iuculano et al., 2014; Soulieres et al., 2010).

METHOD

Participants

Sixty native Dutch-speaking preschoolers (45 boys, 15 girls) with a mean age of 5.92 years (*SD* = 0.28) participated. In the Flemish part of Belgium, children typically attend preschool when they are aged 2.5 years, and enter elementary school at around age 6. Children usually attend preschool for 3 years. Although preschool education is not compulsory, the vast majority of children do attend preschool. In the current study, all children had received three years of preschool education at the moment of testing. All children, although recruited from different schools, attended mainstream educational settings or special education specifically focused on high-functioning children with ASD. Within these two settings, the same *developmental goals* (i.e., a set of basic competencies that need to be acquired at the end of preschool) are set. As such, the children were assumed to receive similar preschool experiences concerning preparatory mathematics.

Children with ASD (25 boys, 5 girls) were recruited through rehabilitation centers, special school services, and other specialized agencies for developmental disorders. They had a formal diagnosis made independently by a qualified multidisciplinary team according to established criteria, such as specified in the *Diagnostic and Statistical Manual of Mental Disorders, 4th edition, Text Revision* (American Psyciatric Association, 2000). This formal diagnosis was confirmed by a score above the ASD cut-off on the Dutch version of the *Social Responsiveness Scale* (*SRS*; Roeyers, Thys, Druart, De Schryver, & Schittekatte, 2011). The Dutch version of the *SRS* has a good internal consistency, with a Cronbach's alpha of .94 for boys and .92 for girls (Roeyers et al., 2011). Scores on the *Autism Diagnostic Observation Schedule* (*ADOS*; Lord et al., 2000) were available for 18 children with ASD. Children with and without *ADOS* scores did not differ significantly on the *SRS*, $U = 79.00$, $p = .232$. In TD children (20 boys, 10 girls), there was no parental concern of developmental problems and all children scored below the ASD cut-off on the *SRS* (Roeyers et al., 2011).

Each participant had a full scale IQ (FSIQ) of 80 or more, measured with the *Wechsler Preschool and Primary Scale of Intelligence – Third edition* (*WPPSI-III*; Wechsler, 2002). As such, the study focused on a group of high-functioning children with ASD. Table 1 provides an overview of the sample characteristics.

Table 1. *Descriptive characteristics of the sample*

	TD (*n* = 30)		ASD (*n* = 30)		Test	
Sex (boys)	20		25		$\chi^2(1) = 2.22$,	$p = .136$
	M	*(SD)*	*M*	*(SD)*		
Age (in years)	5.86	(0.25)	5.98	(0.31)	$U = 344.50$,	$p = .117$
FSIQ[a]	109.03	(11.56)	104.83	(12.36)	$U = 321.50$,	$p = .085$
VIQ[b]	110.53	(10.38)	105.41	(12.95)	$U = 300.50$,	$p = .041$
PIQ[c]	105.60	(11.92)	105.38	(13.52)	$U = 400.00$,	$p = .595$
SES[d]	49.18	(7.19)	46.53	(9.67)	$U = 377.50$,	$p = .283$
SRS (*T*-score)[e]	46.77	(5.06)	85.60	(19.39)	$U = 0.00$,	$p < .001$

Note. Since the sampling distributions of the variables were non-normally distributed, nonparametric analyses were conducted; TD = typically developing children, ASD = children with autism spectrum disorder; [a]Full Scale IQ, measured with *Wechsler Preschool and Primary Scale of Intelligence – Third edition*, [b]Verbal IQ, [c]Performance IQ, [d]Socioeconomic status, measured with the *Hollingshead index*, [e]*T*-score on *Social Responsiveness Scale*.

The two groups were matched on age, FSIQ, sex ratio, and socioeconomic status (SES; measured with the *Hollingshead Four Factor Index of social status*; Hollingshead, 1975) on group level. This index is based on the factors education, occupation, sex, and marital status (Hollingshead, 1975). According to the Hollingshead classification, participants in this study fell, on average, into the upper middle SES group (range 40-54; Hollingshead, 1975).

Materials

Verbal subitizing. The preschoolers' verbal subitizing abilities were tested by means of a computerized enumeration task similar to the one described by Fischer et al. (2008) and based on the stimuli used by Maloney, Risko, Ansari, and Fugelsang (2010). In this task, black squares on a white background were displayed on a 17 inch monitor. Responses were collected using a voice key and were manually put in by the researcher. Each trial began with a central fixation point presented for 500 ms. A display containing one to nine square boxes was then centrally presented at fixation until a vocal response was detected. Participants were instructed to say aloud the number of squares on the screen as quickly and accurately as possible. The individual area, total area, and density of the squares were varied to insure that participants could not use non-numerical cues to make a correct decision (see Dehaene, Izard, & Piazza, 2005; Maloney et al., 2010). There were two practice phases and one test phase. In the first practice phase, the child was presented with five displays of randomly chosen numerosities (varying between one and nine) with a presentation and response time of 5,000 ms, so the stimulus remained visible during response time. The second practice phase consisted of 10 displays of randomly chosen numerosities (varying between one and nine) with a presentation time of 120 ms – in line with the study of Hannula, Räsänen, and Lehtinen (2007) and Fischer et al. (2008) – and a mask of 100 ms. Participants had a total response time of 4,000 ms from presentation of the stimulus onward. The test phase consisted of 72 trials (each numerosity of one to nine was presented eight times) with a presentation time of 120 ms, a mask of 100 ms, and a total response time of 4,000 ms. The short presentation time prevented children from counting the squares to enumerate the items (see Fischer et al., 2008). Both accuracy and mean reaction times (based on correct trials only) were used as outcome variables. Cronbach's alpha was .88 for the subitizing range (1-3), .84 for the counting range (4-9), and .88 for the total range (1-9). The task took approximately 15 minutes to complete. Due to technical problems, the results of one control child were not recorded (n_{TD} = 29). In addition, a child from the ASD group did not comprehend the task, resulting in missing values for this child (n_{ASD} = 29).

Counting. Counting abilities were assessed using two subtests of the *Test for the Diagnosis of Mathematical Competencies* (*TEDI-MATH*; Grégoire, Noël, & Van Nieuwenhoven, 2004). The psychometric value of the battery was tested on a sample of 550 Dutch-speaking Belgian children (Grégoire, 2005). The *TEDI-MATH* has proven to be a conceptually accurate and clinically relevant instrument (Desoete & Grégoire, 2006; Stock, Desoete, & Roeyers, 2007), and its predictive value has been demonstrated in several studies (Desoete & Grégoire, 2006; Desoete et al., 2009). Procedural counting (subtest 1) was assessed using accuracy in counting row and counting forward to an upper bound and/or from a lower bound. The task consisted of eight items and had a maximum raw score of 8. Conceptual counting (subtest 2) was assessed by judging the validity of counting procedures based on the five basic counting principles formulated by Gelman and Galistel (1978). In order to investigate these principles, children had to judge the counting of both linear and nonlinear patterns of objects, and were asked some questions about the counted amounts of objects. Furthermore, they had to construct two numerically equivalent amounts of objects and use counting as a problem-solving strategy in a riddle. The maximum total raw score for this subtest was 13. Cronbach's alpha was .73 for procedural counting and .85 for conceptual counting. The task took approximately 15 minutes to complete.

Magnitude comparison. A computerized magnitude comparison task, based on the work of Halberda and Feigenson (2008) and Inglis, Attridge, Batchelor, and Gilmore (2011), was used to test this early numerical competency. In each trial, two displays of black dots on a white background were presented simultaneously on a 17 inch monitor. On top of the two displays, an illustration of a sun and a moon were presented. Participants were instructed to press the sun- or the moon-button corresponding to the largest numerosity on a response box as quickly and accurately as possible. Six different ratios were presented. When dividing the smallest by the largest numerosity, these ratios were: .33, .50, .67, .75, .80, and .83. The individual area, total area, and density of the squares were varied to insure that participants could not use non-numerical cues to make a correct decision (see Dehaene et al., 2005). There were two practice phases and one test phase. In the first practice phase, the child was presented with five trials of randomly chosen numerosities with a presentation time of 5,000 ms, a mask of 1,000 ms, and a total response time of 6,000 ms. The presentation of the stimuli was preceded by a display with two fixation crosses lasting for 500 ms. The second practice phase consisted of 10 displays of randomly chosen numerosities with a fixation time of 500 ms, a presentation time of 1,200 ms, a mask of 2,800 ms, and a total response time of 4,000 ms from presentation onward. In between trials, a blank screen appeared for 500 ms. The test session consisted of 72 trials (each ratio was presented twelve times) with a fixation time of 500 ms, a presentation time of 1,200 ms, a mask of 2,800 ms, and a total response time of 4,000 ms. Both accuracy and mean reaction times (based on correct trials only) were used as outcome variables. Cronbach's alpha was .80 for the total task. The task took approximately 15 minutes to complete. Due to technical problems, the results of one control child were not recorded (n_{TD} = 29).

Estimation. Estimation was tested by means of a 0-100 number line task based on the task of Siegler and Opfer (2003) and Siegler and Booth (2004). Children were presented 25 cm long lines in the center of white A4 sheets. Each line was seen separately from the others. The left end anchor of the number line was labeled by 0 and the right by 100, the number to be positioned appeared 2 cm above the center of the line. Stimuli were presented in three different formats. In the visual Arabic format, stimuli were presented as Arabic numerals (e.g., anchors 0 and 100, target number 2); target numbers were not read out. In the auditory-verbal format, stimuli were presented as spoken number words (e.g., anchors zero and hundred, target number two), and in the analog magnitude format, stimuli were presented as dot patterns (e.g., anchors of zero dots and hundred dots, target number two dots). The dot patterns consisted of black dots in a white disc. Dot patterns were controlled for perceptual variables using the procedure of Dehaene et al. (2005), meaning that on half of the trials the dot size was held constant, while on the other half, the size of the total occupied area of the dots was held constant.

When composing the task, both the format of the target numbers as well as the presented numerosities were chosen randomly. However, once determined, this order was the same for each participant. Children were asked to put a single mark on the line to indicate the location of the number. Although the instructions could be rephrased if needed, no feedback was given to the participants regarding the accuracy of their marks. The task consisted of 3 practice trials (for which the numerosities were randomly chosen between 1 and 99) and 30 test trials using the following 10 target numbers in all three presentation formats: 2, 3, 4, 6, 18, 25, 42, 67, 71, and 86 (corresponding to sets A and B in Siegler & Opfer, 2003). The percentage of absolute error (PAE) was calculated per child as a measure of children's estimation accuracy, following the formula of Siegler and Booth (2004).

Next to PAE, the underlying representation (linear or logarithmic) of the estimates was also investigated. In order to do this on group level, the procedure of Siegler and Opfer (2003) was used. Regression analyses on the group median estimates (plotting median estimates against the actual to be estimated values) were used to compute both linear and logarithmic fits (R^2 values) for the TD children and the children with ASD. The difference between the linear and logarithmic regression models was tested with a paired samples t-test. First, the absolute difference between the median estimate for each number and the predicted values based on the linear and logarithmic model respectively was calculated, resulting in the absolute values of the residuals of the linear and logarithmic fit. Next, the paired samples t-test was executed to determine if the residuals of the linear and logarithmic fit differed significantly from each other. On individual level, following the procedure of Berteletti, Lucangeli, Piazza, Dehaene, and Zorzi (2010), each child was attributed the best fitting significant model between linear and logarithmic. A child was classified as not having a valid representation when both linear and logarithmic coefficients failed to reach significance or when slopes were negative (indicating an inverse relationship as the one to be expected).

Cronbach's alpha was .87 for the total task. The task took approximately 15 minutes to complete. Two TD children and one child with ASD were excluded from the analyses (n_{TD} = 28, n_{ASD} = 29), as they did not understand the task properly, which was indicated by the lack of any variation in their estimates of all numbers (i.e., positioning all estimates in the middle or positioning all estimates at one anchor).

Arithmetic operations. Arithmetic operations were assessed using a subtest of the *TEDI-MATH* (Grégoire et al., 2004). A series of six visually supported addition and subtraction exercises was presented to all children (subtest 5.1). The maximum total raw score was 6. Cronbach's alpha of this subscale was .85. The task took approximately 5 minutes to complete.

Procedure

The study was approved by the authorized ethical committee of the Faculty of Psychology and Educational Sciences of Ghent University. Parents received an information letter and signed an informed consent before their participation. Children were assessed individually, but the tests were presented in the same order for all children. It took approximately two hours for participants to complete the test battery. The assessment was spread over two different test sessions. In the first session, children were assessed with the *WPPSI-III* (Wechsler, 2002) and with the computerized tasks (verbal subitizing and magnitude comparison). During the second session, children were assessed with the *TEDI-MATH* tasks (counting and arithmetic operations) and the number line task (estimation). All test leaders (graduate students) received training in the assessment and interpretation of the tests.

Analyses

First, data were examined for patterns of normality. As the group size of the ASD and TD subgroups was lower than 50, a Shapiro-Wilk test was performed to assess the normality of the sampling distribution for the different dependent variables (Field, 2009). In cases where the assumptions for normal distribution were violated ($p < .050$), nonparametric analyses were conducted. Otherwise, parametric analyses were used.

Second, the correlations between early numerical competencies, FSIQ, and severity of ASD symptomatology (using the *SRS* score; Roeyers et al., 2011) were examined.

In a next step, children with ASD and TD children were compared on the five early numerical competencies. For verbal subitizing, graphical inspection of the data revealed an *end effect* (guessing) for numerosities 7 until 9, which were therefore excluded from statistical analyses (e.g., Schleifer & Landerl, 2011; Simon, Peterson, Patel, & Sathian, 1998). The reaction times of the two groups were then compared using a repeated measures analysis with numerosity as within-subject factor and group as between-subject factor. This was first done for the 1-6 range and repeated more specifically for the subitizing range (1-3). Because only correct trials were included in the reaction time analyses, the degrees of freedom for the 1-6 analysis were lower than for the 1-3 analysis (as a lot of children obtained no correct responses for the larger numerosities, whereas all of them had at least one correct response for the numerosities within the subitizing range). For accuracy, the same analyses were executed, but using the nonparametric variants (as the sampling distributions did not meet the assumption of normality): a Friedman ANOVA to investigate the effect of numerosity, and Mann-Whitney U tests to compare TD and ASD groups for the 1-6 range and the 1-3 range. For counting, Mann-Whitney U tests were used to compare the two groups on procedural and conceptual counting knowledge. For magnitude comparison, a Friedman ANOVA was used to investigate the main effect of ratio and a Mann-Whitney U test was used to compare children with and without ASD. This was done for both reaction time and accuracy. For estimation, a Friedman ANOVA was used to investigate the main effect of presentation format. Mann-Whitney U tests were used to compare the PAEs between TD and ASD groups. Underlying representations were first examined on group level, for the TD and ASD group separately. This was done by comparing the linear and logarithmic fits with a paired samples t-test for the overall number line task, as well as for the separate presentation formats. At individual level, each child was categorized into one of the following categories: linear representation, logarithmic representation, and no valid representation. A Fisher exact test was used to determine whether allocation to these groups differed between TD and ASD children. For arithmetic operations, a Mann-Whitney U test was used to compare the performance of the two groups of preschoolers.

RESULTS

Correlation analysis

Table 2 provides an overview of the correlations between all variables. Significantly different correlation patterns seemed to emerge for TD children and children with ASD for some of the variables (Fisher r-to-z transformations, $p < .050$). In most of these cases, stronger relationships between the constructs were observed in the ASD group. In addition, some significant correlations were found within the ASD group between ASD symptom severity (measured with the *SRS*; Roeyers et al., 2011) on the one hand and counting and arithmetic operations on the other hand.

Table 2. *Correlations between early numerical competencies, full scale IQ, and severity of ASD symptomatology*

		VS[a]		C[d]		MC[g]		E[h]	AO[j]	FSIQ[k]
		RT[b] (1-3)	ACC[c] (1-3)	PC[e]	CC[f]	Overall RT[b]	Overall ACC[c]	Overall PAE[i]		
VS[a]										
RT[b] (1-3)	**TD**	**-**								
	ASD	-								
ACC[c] (1-3)	**TD**	**-.06**	**-**							
	ASD	-.60***	-							
C[d]										
PC[e]	**TD**	**-.26**	**.10**	**-**						
	ASD	-.53**	.30	-						
CC[f]	**TD**	**-.47***	**.42***	**.45***	**-**					
	ASD	-.21	.29	.58***	-					
MC[g]										
Overall RT[b]	**TD**	**-.19**	**.36**^{t}	**.27**	**.37***	**-**				
	ASD	-.04	.02	-.19	-.05	-				
Overall ACC[c]	**TD**	**-.20**	**.12**	**.28**	**.08**	**.33**^{t}	**-**			
	ASD	-.13	.28	.16	.28	.04	-			
E[h]										
Overall PAE[i]	**TD**	**.29**	**-.16**	**-.26**	**-.33**^{t}	**-.10**	**-.25**	**-**		
	ASD	.33^t	-.44*	-.11	-.17	.24	-.47**	-		
AO[j]	**TD**	**-.09**	**.35**^{t}	**-.11**	**.37***	**.31**^{t}	**.10**	**-.44***	**-**	
	ASD	-.49**	.40*	.59***	.49**	.03	.19	-.17	-	
FSIQ[k]	**TD**	**-.04**	**.02**	**-.07**	**.03**	**-.12**	**.16**	**-.43***	**.19**	**-**
	ASD	-.37^t	.21	.58***	.52**	.05	.31	-.22	.44*	-
SRS[l]	**TD**	**-.18**	**.34**^{t}	**.16**	**.11**	**.22**	**.13**	**-.18**	**.08**	**.20**
	ASD	.31	-.23	-.44*	-.25	.28	.07	.20	-.37*	-.22

Note. $^t p < .100$, *$p < .050$, **$p < .010$, ***Bonferroni-corrected ($p < .001$); underlined correlations indicate a significantly stronger correlation than in the other group (Fisher r-to-z transformation, $p < .050$); TD = typically developing children, ASD = children with autism spectrum disorder; [a]Verbal subitizing, [b]Reaction time, [c]Accuracy, [d]Counting, [e]Procedural counting, [f]Conceptual counting, [g]Magnitude comparison, [h]Estimation, [i]Percentage of absolute error, [j]Arithmetic operations, [k]Full scale IQ, [l]Raw score on *Social Responsiveness Scale.*

Verbal subitizing

For reaction times, a repeated measures analysis with numerosity (1-6) as within-subject factor and group as between-subject factor revealed a strong main effect of numerosity, $F(5,25) = 20.02$, $p < .001$, indicating a significant increase in reaction time for increasing numerosities. However, no significant main effect of group, $F(1, 29) = 2.09$, $p = .159$, or group × numerosity interaction, $F(5, 25) = 0.64$, $p = .671$, was found, as the reaction times of ASD and TD children mostly overlapped (see Figure 1). When focusing specifically on the subitizing range (1-3), there was no significant difference in mean reaction time between TD children and children with ASD, $F(1, 56) = 0.33$, $p = .570$.

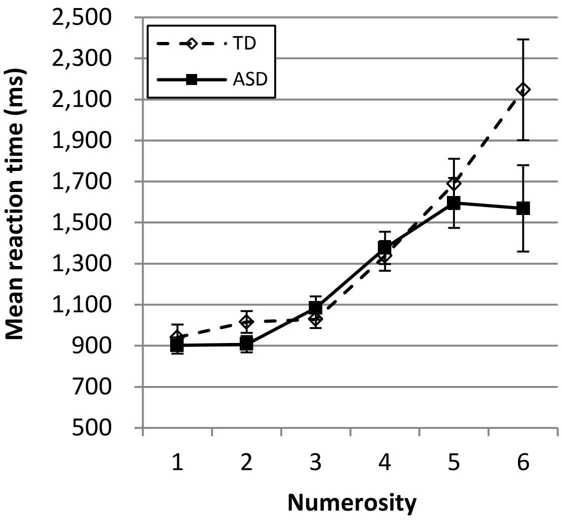

Figure 1. Verbal subitizing – Reaction time in function of numerosity.
Note. TD = typically developing children; ASD = children with autism spectrum disorder.

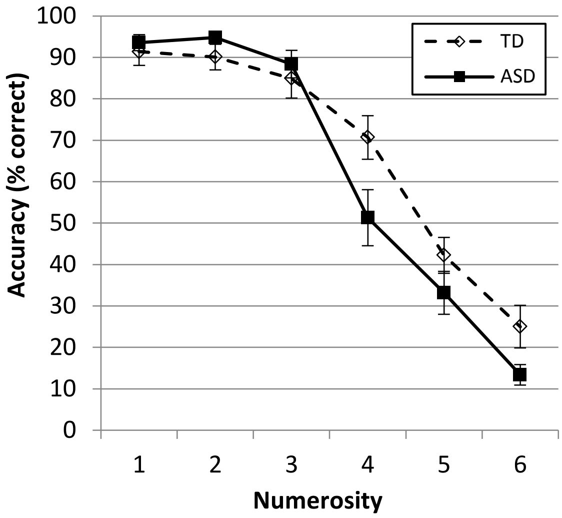

Figure 2. Verbal subitizing – Accuracy in function of numerosity.
Note. TD = typically developing children; ASD = children with autism spectrum disorder.

When considering the accuracy data, a Friedman ANOVA demonstrated a significant main effect of numerosity, $\chi^2(5) = 226.13$, $p < .001$, with lower accuracy rates for increasing numerosities. Moreover, a Mann-Whitney U test showed a trend for a difference in total accuracy between the two groups, $U = 307.50$, $p = .078$ (see Figure 2). Separate Mann-Whitney U tests for the different numerosities showed only a significant (not Bonferroni-corrected) difference at numerosity four, $U = 289.00$, $p = .039$, with a lower accuracy score for children with ASD compared to TD children. When focusing specifically on the subitizing range (1-3), there was no significant difference in accuracy between TD children and children with ASD, U = 419.50, p = 987.

Counting

A Mann-Whitney U test revealed no significant difference in the procedural counting knowledge of children with ASD and TD children, U = 345.00, p = .111 (see Figure 3).

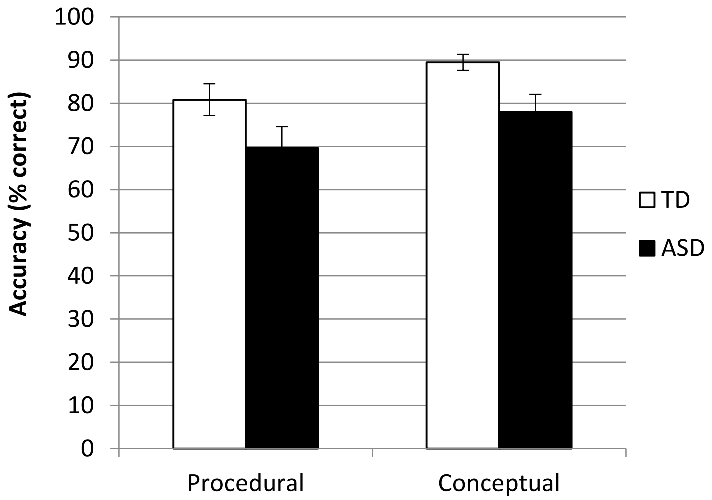

Figure 3. Counting – Accuracy for procedural and conceptual counting knowledge. *Note.* TD = typically developing children; ASD = children with autism spectrum disorder.

However, there was a trend for a difference in the conceptual counting knowledge between the two groups, U = 329.00, p = .067, with children with ASD showing a trend toward lower conceptual counting knowledge than TD children (see Figure 3).

Magnitude comparison

For reaction times, a Friedman ANOVA demonstrated no significant main effect of ratio, $\chi^2(5)$ = 7.72, p = .173. Moreover, a Mann-Whitney U test showed no significant difference in reaction times between both groups, U = 403.00, p = .628 (see Figure 4).

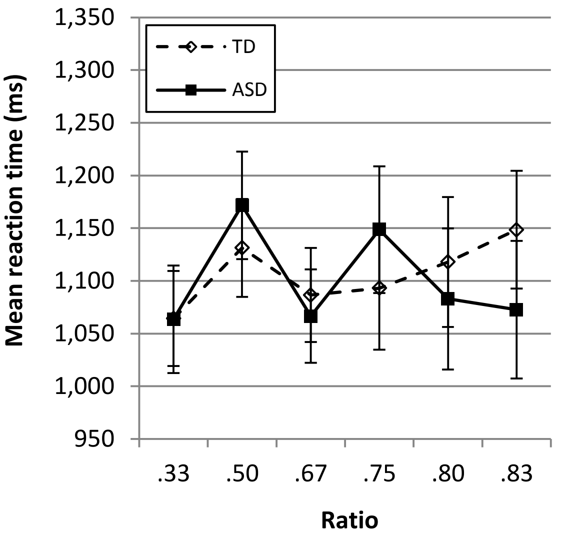

Figure 4. Magnitude comparison – Reaction time in function of ratio.
Note. TD = typically developing children; ASD = children with autism spectrum disorder.

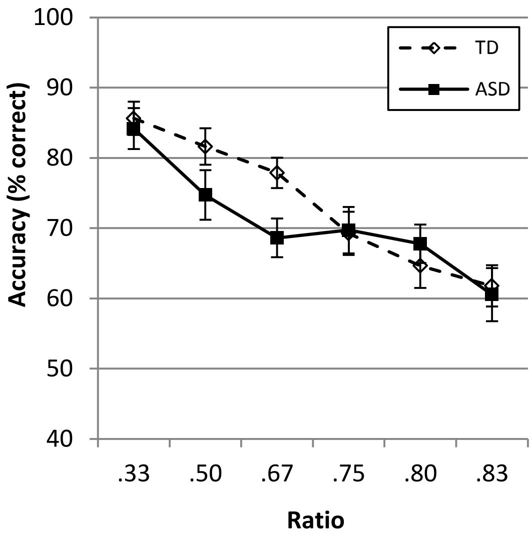

Figure 5. Magnitude comparison – Accuracy in function of ratio.
Note. TD = typically developing children; ASD = children with autism spectrum disorder.

For the accuracy data – as opposed to the reaction time data – there was a significant main effect of ratio, $\chi^2(5) = 103.30$, $p < .001$, with lower accuracy rates for larger ratios. However, a Mann-Whitney U test showed no significant differences in total accuracy between the two groups, $U = 399.50$, $p = .590$ (see Figure 5).

Estimation

In a first step, differences in PAEs between the three presentation formats were examined. A Friedman ANOVA demonstrated no differences in accuracy between the three presentation formats, $\chi^2(2) = 1.24$, $p = .539$ (see Figure 6).

Second, group differences in PAEs were investigated. Mann-Whitney U tests indicated no significant differences between both groups, neither for the total task (averaging across formats), $U = 315.00$, $p = .146$, nor for the separate formats ($p > .050$; see Figure 6).

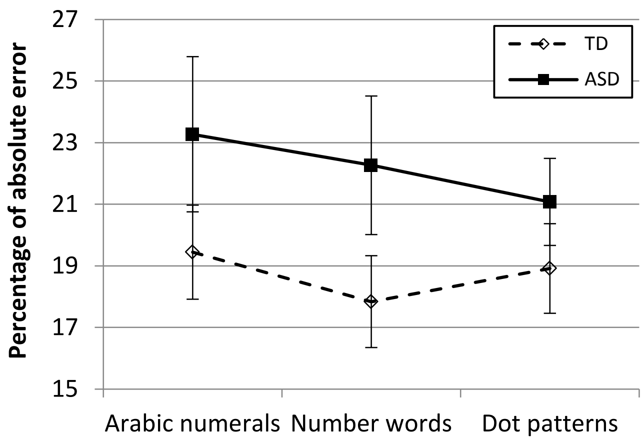

Figure 6. Estimation – Percentages of absolute error in function of format. *Note.* TD = typically developing children; ASD = children with autism spectrum disorder.

Next, the underlying representation was examined, both at the group and individual level. At group level, the best fitting representational model for the overall number line task was logarithmic for the TD group (R^2_{log} =.96, p <.001), and did significantly differ from the model with the best linear fit (R^2_{lin} =.75, p = .001), t(9) = 3.95, p = .003 (see Figure 7). For the ASD group, the fit for the logarithmic model was also the best (R^2_{log} =.92, p <.001). There was a trend for a difference from the linear fit (R^2_{lin} =.74, p = .001), t(9) = 2.04, p = .072 (see Figure 8).

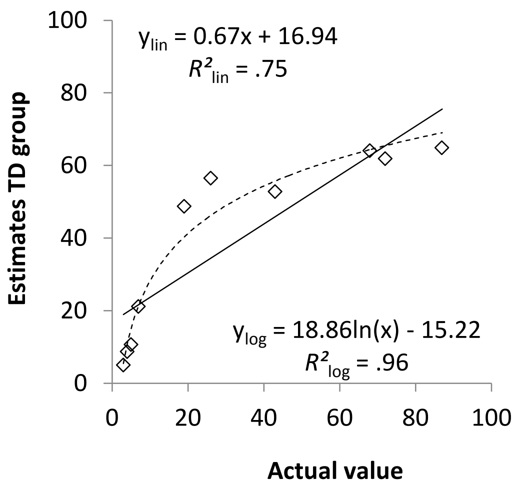

Figure 7. Estimation – Linear and logarithmic fit of typically developing (TD) children.

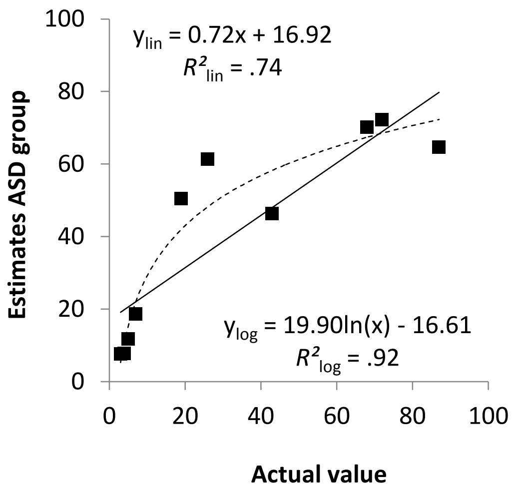

Figure 8. Estimation – Linear and logarithmic fit of children with autism spectrum disorder (ASD).

This same pattern of results was reflected when looking at the Arabic numeral format and the number word format. For dot patterns, however, the logarithmic model still provided the best fit for both groups but it did not significantly differ from the best linear fit, $t(9) = 0.85$, $p = .418$ in the TD group and $t(9) = 0.71$, $p = .495$ in the ASD group respectively. The mean linear and logarithmic determination coefficients were both quite high in the TD group (.77 and .85 respectively), whereas they were low for the ASD group (.43 and .53 respectively). Mann-Whitney U tests revealed indeed (marginally) significant lower linear and logarithmic R^2 values for children with ASD compared to TD peers, $U = 251.00$, $p = .013$ and $U = 283.50$, $p = .051$ respectively.

At the individual level, no significant differences between groups, Fisher exact test, $p = .168$, were found between the allocation to the following categories: no valid representation (TD: 3.57%; ASD: 17.24%) – logarithmic representation (TD: 92.86%; ASD: 72.41%) – linear representation (TD: 3.57%; ASD: 10.34%). These results were replicated for the separate formats.

Arithmetic operations

A Mann-Whitney U test revealed no significant difference in the ability to execute arithmetic operations between children with ASD and TD children, $U = 449.50$, $p = .994$ (see Figure 9).

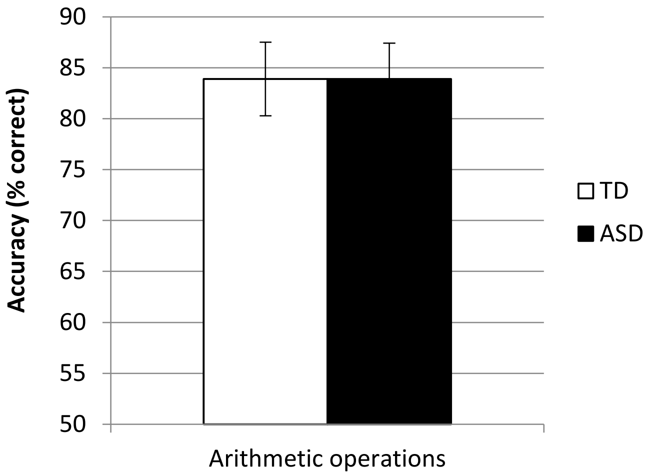

Figure 9. Arithmetic operations – Accuracy rates.

Note. TD = typically developing children;
ASD = children with autism spectrum disorder.

DISCUSSION

The main objective of this study was to provide an exploratory analysis of five early numerical competencies – adopted from the work of N. C. Jordan and Levine (2009) – of children with ASD, indicating possible strengths or weaknesses compared to TD children within the domain of mathematics at preschool age (5-6 years). In doing so, we wanted to address the concerns raised by practitioners at an early age and contribute to the existing literature, which is scarce and inconclusive to date.

Overall, the current study revealed no significant differences between the two groups of preschoolers, indicating very similar early number processing in children with and without ASD before entering elementary school. This finding is consistent with some of the previous studies that also investigated the mathematical abilities of children with ASD from a between-group perspective, but at a later age (Chiang & Lin, 2007; Gagnon et al., 2004; Iuculano et al., 2014; Jarrold & Russell, 1997). However, despite the overall similarities between the two groups, some downward trends in the performance of children with ASD were found for verbal subitizing accuracy and conceptual counting knowledge. Given the small sample size and the fact that verbal subitizing and counting have proven to be predictive for later mathematics performance in children with ASD (Titeca et al., 2014), it is important to mention these marginally significant results. The following sections provide an overview of the general findings for the different numerical competencies, along with the strengths, limitations, and implications of the current study.

General findings

Correlation analysis. For the majority of the early numerical competencies, only small to medium correlations could be observed. As Dowker (2008) concluded, numerical ability is not a unitary concept, meaning that individual differences on one task are not necessarily highly related to individual differences on others. It is worth noting that different correlation patterns emerged for TD children and children with ASD for some of the variables. In most of these cases, stronger relationships between the constructs could be observed in the ASD group. For example, FSIQ and early numerical competencies (especially counting) seem to be more strongly related in children with

ASD than in TD children. Moreover, some significant correlations could be observed between ASD symptom severity (measured with the *SRS*; Roeyers et al., 2011) and counting or arithmetic operations. Together with the aforementioned downward trends, these correlations might suggest that autism-specific information processing characteristics exert their influence on mathematics performance (cf. infra). However, further (longitudinal) research with larger groups of children is needed to clarify the exact meaning of these findings.

Verbal subitizing. Just as in TD children, there was an increase in reaction time and a decrease in accuracy in function of increasing numerosity in children with ASD, resulting in the observation of the typical *elbow effect* (Dehaene, 1992). Although no significant differences could be found between the two groups for reaction times, children with ASD showed a trend toward less accurate scores for enumerating numerosity four when compared to TD children. This is in contrast with previous studies demonstrating no differences with TD children in accuracy rates on verbal subitizing tasks (Gagnon et al., 2004; Jarrold & Russell, 1997). However, the children in our sample (5-6 years) were younger than the individuals in the studies of Gagnon et al. (2004) and Jarrold and Russell (1997), who investigated participants aged 10-21 years and 6-18 years respectively. This could imply that the subitizing skills in our young age group are still developing (Chi & Klahr, 1975). As such, the observed difference might perhaps – due to individual variation in the subitizing range – be explained by the fact that more children in the TD group than in the ASD group managed to subitize until numerosity four. This may point to a limited capacity to overview multiple stimuli at once in children with ASD and, hence, a weaker central coherence. Surely, due to the restricted presentation time of the stimuli (i.e., 123 ms), the use of a serial counting strategy (cf. Gagnon et al., 2004; Jarrold & Russell, 1997) may have been less successful and thus resulting in lower accuracy scores on the enumeration task in our study.

Counting. This study suggests that whereas children with ASD are comparable to TD children concerning their procedural counting knowledge, they show a somewhat lower conceptual counting knowledge. Conceptual (counting) knowledge involves interconnected and meaningful knowledge (Baroody, 2003; Hiebert & Lefevre, 1986). This finding can be connected to the line of research indicating that individuals with ASD show a distinction between preserved mechanical or procedural skills and impaired conceptual skills, with the latter requiring more complex information processing, reasoning, and logical analysis (Goldstein et al., 1994; Minshew, Goldstein, & Siegel, 1995; Minshew et al., 1994). This differentiation between procedural and conceptual skills in children with ASD can be explained by the central coherence account (Frith & Happé, 1994; Noens & van Berckelaer-Onnes, 2005). The drive for central coherence seen in TD individuals helps them to make sense of something and to extract meaning, whereas the preferred focus on details in children with ASD might jeopardize such adequate sense-making (Noens & van Berckelaer-Onnes, 2005). Although these findings were only demonstrated for the field of literacy (Goldstein et al., 1994; Minshew et al., 1994), the current study suggests that this line of reasoning might be extrapolated to the field of mathematics.

Magnitude comparison. In line with previous research (e.g., Moyer & Landauer, 1967), results on the magnitude comparison task showed a *ratio dependent* performance profile, demonstrated in the form of a decrease in accuracy in function of ratio. For both reaction time and accuracy, no significant differences could be found between the performances of children with ASD and TD children. This suggests that the results of the case study of Soulieres et al. (2010), who reported enhanced magnitude comparison skills in two 9-year-olds with ASD, cannot be generalized to all children with ASD.

Estimation. The mean observed PAEs (18% - 22%) were, despite a different operationalization (i.e., three presentation formats instead of one), similar to those of the preschoolers of comparable age in the studies of Berteletti et al. (2010), Booth and Siegler (2006), and Siegler and Booth (2004): 23%, 24%, and 24% respectively. Moreover, the number line performance of preschool children on a 0-100 interval was best represented by a logarithmic model, which also aligns with previous studies (Berteletti et al., 2010; Booth & Siegler, 2006; Siegler & Booth, 2004). No significant group differences could be found in estimation accuracy. In addition, there were no significant differences between the PAEs of the three presentation formats. However, when considering the underlying representations, it seems nonetheless recommended to take notice of the separate presentation formats in future research. First of all, in both groups of children, all presentation formats except for the dot patterns were best represented by a logarithmic model. For dot patterns, the logarithmic and linear fits did not differ significantly from each other in either group of children. It should be noted that, whereas in the TD group the logarithmic and linear determination coefficients were both high, neither the linear nor the logarithmic fit seemed appropriate for the estimates of the ASD group. R^2 values for children with ASD were significantly lower compared to TD peers. Second, the categorization of individual representations, although not significant, confirmed that a large part of the ASD children showed no valid representation for their estimates of dot patterns. Our findings indicate that, whereas TD children start to acquire the abilities to use a linear strategy for representing dot patterns on a number line, children with ASD show most problems with this presentation format. These difficulties of children with ASD could be due to problems with estimating nonsymbolic stimuli on the number line, which was supported by the qualitative observation that children with ASD felt unsure when needed to give an approximate answer, without the possibility to exactly determine the amount of dots by counting. A focus on the separate dots may have hampered the children from making sense of the pattern as a whole, again reflecting the possible influence of a weaker central coherence in children with ASD (Frith, 1989). Additional research is however needed to investigate this assumption.

Arithmetic operations. Results indicated no significant differences between children with ASD and TD children. The fact that the exercises were visually supported may have been beneficial for both groups of children, as previous research indicated that preschoolers experience difficulties with solving story problems that are solely verbally presented (Levine, Jordan, & Huttenlocher, 1992). The children from the ASD group may have relied even more on these visually presented stimuli. Visual support can help direct the attention of the child with ASD to the relevant stimuli within a task, thereby helping to organize and process the given information (Hayes et al., 2010).

Strengths and limitations

Previous studies on mathematical abilities in children with ASD are scarce and investigate mostly older children or adolescents. The current study provides valuable insights into the important developmental period of preschool age as a transition period in which numbers become increasingly important. Because early numerical competencies are predictive for later mathematics, studying these precursors that serve as a foundation for later mathematics performance can be informative. Moreover, the current study adds to previous literature by using a multicomponential approach instead of incorporating only one composite math score (e.g., Chiang & Lin, 2007) or focusing on one single aspect of mathematics (e.g., Gagnon et al., 2004). Recent studies strongly advocate the inclusion of several components of mathematics into one study (e.g., J. A. Jordan et al., 2009). The use of a multicomponential approach enables researchers to obtain a more meticulous view on the mathematical abilities of children with ASD, since it is possible to compare children with and without ASD on several components. After all, the inclusion of only one component or the use of a math composite score might be misleading, as different results were established for the different components of mathematics in our study. In addition, the use of a matched control group instead of the normed samples of standardized achievement tests allows for a more reliable and direct comparison between children with ASD and TD children.

However, given our small sample size, the results of the current study should be interpreted with care. When analyses have insufficient power and are not significant, a risk of type 2- or β-mistakes cannot be excluded (Field, 2009). Indeed, some figures suggest that certain differences might turn significant when using a larger sample size. Moreover, the current study only included high-functioning children with ASD, stemming from a high socioeconomic background. Additional studies on lower functioning children with ASD, with a larger variety in socioeconomic background, are indicated to investigate whether our results could be generalized to the whole population of children with ASD. Within this context of a highly selective and small sample, the suggested recommendations are also tentative, as they can not be extrapolated to the ASD population in general without conducting further research. In addition, the current study investigated the early numerical competencies of children with ASD from a between-group perspective using a group-level approach. Because ASDs are known to be highly heterogeneous (e.g., Estes, Rivera, Bryan, Cali, & Dawson, 2011; Georgiades et al., 2013), future research should look for possible subgroups of children by conducting within-group studies using cluster analyses on larger groups of children. Since average scores may mask subgroups of individuals with remarkable poor or excellent skills (C.R.G. Jones et al., 2009), a within-group approach would be of added value to our between-group approach. Furthermore, we intentionally chose for research on a behavioral level in the current study, trying to provide an exploratory analysis of possible differences in early numerical competencies between TD children and children with ASD. Based on our findings, we tried to infer some statements on the cognitive theories. However, future research explicitly taking into account these autism-specific information processing characteristics is needed to investigate the value of the cognitive theories in explaining mathematics performance. Finally, it is important to note that most of the instruments have never been used in an ASD group before (except for verbal subitizing and magnitude comparison tasks). However, the *TEDI-MATH* is a standardized measure that is well-validated in Belgium (Grégoire et al., 2004), and the other competencies (verbal subitizing, magnitude comparison, and number line estimation) are operationalized similar to previous research on this topic, resulting in similar effects (elbow effect for the subitizing task, ratio dependency for the magnitude comparison task, similar PAE scores and curve shapes for the number line estimation task). All measures are frequently used in TD populations or children with MLD (e.g., Berteletti et al., 2010; Ceulemans et al., 2014; Praet, Titeca, Ceulemans, & Desoete, 2013; Stock et al., 2007).

Implications

Because no robust significant differences could be identified, it can be concluded that the foundation of mathematical development in high-functioning children with ASD is rather similar to that of TD children. Given the pervasiveness of the condition of ASD on other domains of functioning (G. Jones, 2006), it is encouraging to know that no general deficits in early numerical competencies could be observed. As such, this will be an important message to communicate to parents and teachers. However, the concerns of practitioners are not entirely without foundation, as some trends for lower scores on verbal subitizing accuracy and conceptual counting knowledge were observed, as well as some descriptive differences between children with ASD and TD children (correlation patterns, estimation of dot patterns). Since verbal subitizing and counting are known to be predictive for first grade mathematics in children with ASD (Titeca et al., 2014), these trends might be predictors of concerns for older children. As such, future research is warranted in order to investigate whether these trends turn significant when including larger groups of children. Moreover, it will be important to investigate which autism-specific information processing characteristics might have an influence on mathematics performance. In the same sense, it should be investigated whether children with ASD benefit from instructional adaptations targeted at ameliorating performance on those early numerical competencies with a trend toward weaker scores. Given our findings, it is not inconceivable that the cognitive style of children with ASD – and more specifically, the weaker central coherence – would be a good candidate to be targeted in such adaptations. Children with ASD, but also TD children, might benefit from explicit instruction when dealing with new material or from the provision of visual support, in order to facilitate the connection of important ideas and to overcome problems with weaker central coherence (Fleury et al., 2014).

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CHAPTER 4

MATHEMATICAL ABILITIES IN ELEMENTARY SCHOOL CHILDREN WITH AUTISM SPECTRUM DISORDER[1]

ABSTRACT

Although clinical practitioners often express concerns on the mathematical functioning of children with autism spectrum disorder (ASD), the field of mathematics remains a relatively unexplored topic in individuals with ASD. Moreover, research findings are fragmentary and hold inconclusive results. The present study examined whether grade 1 to 4 elementary school children with ASD scored significantly different from age-adequate norms on mathematics. To this end, a multicomponential approach of mathematics was used. Four domains of mathematics were assessed in 121 children with ASD: procedural calculation, number fact retrieval, word/language problems, and time-related competences. All children attended general education classrooms, following the standard curriculum, and were coached through integrated educational services. Children with ASD showed a strength in word/language problems in second and fourth grade compared to the normed samples. There was evidence of a weakness for procedural calculation in first grade and for time-related competences in first and third grade. In all other cases, average scores were demonstrated. As such, results showed a profile of strengths, average abilities, and weaknesses in mathematics and highlighted the importance of focusing on different domains of mathematics. Since a high variability in mathematical performance was observed, we recommend an individual assessment when considering the mathematical trajectory of children with ASD.

[1] Based on Titeca, D., Roeyers, H., Loeys, T., Ceulemans, A., & Desoete, A. (submitted). Mathematical abilities in elementary school children with autism spectrum disorder. *Infant and Child Development.*

INTRODUCTION

Despite the growing trend to include children with *autism spectrum disorder* (*ASD*) in mainstream educational settings (Harrower & Dunlap, 2001; Whitby & Mancil, 2009), the academic trajectory of these children does not always seem to run smoothly (Balfe, 2001; Lanou, Hough, & Powell, 2012). Within clinical practice, teachers and therapists often consider mathematics as one of the difficult subject matters for children with ASD (Department for Education and Skills, 2001; van Luit, Caspers, & Karelse, 2006). However, the domain of mathematics remains relatively unexplored in children with ASD as yet. Moreover, the few existing studies on this topic present ambiguous results, leaving the issue unsettled.

First, several authors have put forward an enhanced mathematics performance in children with ASD compared to typically developing (TD) peers. Both anecdotal and descriptive research mentioned superior mathematical abilities in individuals with ASD (Baron-Cohen, Wheelwright, Burtenshaw, & Hobson, 2007; Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001; Sacks, 1986), and also some empirical studies provided evidence that points into this direction (Iuculano et al., 2014; Jones et al., 2009). Jones et al. (2009), for example, demonstrated that an IQ-mathematics discrepancy in which mathematics exceeds general intellectual capacities (16.2% of the cases) is far more common than the opposite pattern (6.1% of the cases), suggesting a cognitive strength in mathematics. Iuculano et al. (2014) came to a similar conclusion when reporting better numerical problem-solving abilities in elementary school children with high-functioning autism than in TD peers.

In contrast, other studies have documented mathematical problems in children with ASD. A limited number of comorbidity studies (Mayes & Calhoun, 2006; Reitzel & Szatmari, 2003) showed that the prevalence of *mathematical learning disorders* (*MLDs*) in children with ASD (varying from 12% to 46%) exceeded the prevalence of MLD in the general school-aged population, which is – although varying considerably depending on the criteria and measures (Mazzocco, 2007) – traditionally estimated between 2% and 14% (e.g., American Psychiatric Association [APA], 2013; Barbaresi, Katusic, Colligan, Weaver, & Jacobsen, 2005; Shalev, Manor, & Gross-Tsur, 2005). Moreover, several studies considered mathematics as a cognitive weakness, with a performance below cognitive abilities in a substantial subgroup of children with ASD (Chiang & Lin, 2007; Mayes & Calhoun, 2003). Mayes and Calhoun (2003) reported that 22% of the high-functioning individuals with ASD showed a significant IQ-math discrepancy. Chiang and Lin (2007) made a review which included 18 articles and found that performance on the Arithmetic subtest of the *Wechsler Intelligence Scale* (Wechsler, 1991) was significantly lower than the average of all subtest scores, although they evaluated the clinical significance of this finding as being small.

Finally, some studies argue for average or similar mathematical abilities in children with ASD when compared to the normed population or with TD peers. Chiang and Lin (2007), for example, reported this finding in their review comparing individuals with ASD to the normed population. Although Iuculano et al. (2014) reported enhanced numerical problem-solving abilities in elementary school children with ASD, their word/language problems were found to be average in comparison with TD peers.

The divergence in findings may, amongst others, be attributed to differences in focus (mathematical processes [e.g., Gagnon, Mottron, Bherer, & Joanette, 2004] versus outcomes [e.g., Chiang & Lin, 2007]); perspective (within-group [e.g., Mayes & Calhoun, 2003] versus between-group [e.g., Iuculano et al., 2014]); level of research (behavioral [e.g., Jones et al., 2009] versus neurobiological [e.g., Iuculano et al., 2014]); age (elementary school children [e.g., Iuculano et al., 2014] versus adolescents [e.g., Jones et al., 2009]); or reported mathematical abilities (composite score [e.g., Chiang & Lin, 2007] versus a multicomponential approach [e.g., Titeca, Roeyers, Josephy, Ceulemans, & Desoete, 2014]). This being the case, more research is warranted to disentangle the inconsistencies and to replicate previous findings on mathematics in children with ASD.

Mathematical abilities in elementary school

The present study focuses on the *mathematical abilities* of elementary school children with ASD. Although mathematics in elementary school is culturally dependent, several vital subcomponents seem to be involved in its adequate development (Geary, 2000).

Based on the work of Geary (2000, 2004), four important domains of mathematics can be identified: procedural calculation, number fact retrieval, word problems, and visuospatial abilities. *Procedural calculation* is needed to solve arithmetic problems, converting numerical information into mathematical equations and algorithms (Dowker, 2005). By executing arithmetic problems repetitively, basic number facts are retained in long-term memory and automatically retrieved if needed, termed as *number fact retrieval* (Geary, 2000). The domain of *word problems*, in our study referred to as *word/language problems*, is associated with verbal problem-solving abilities (Geary, 2000; Meyer, Salimpoor, Wu, Geary, & Menon, 2010). The role of language in the prediction of numeracy development has recently been stressed in several studies (e.g., Negen & Sarnecka, 2012; Praet, Titeca, Ceulemans, & Desoete, 2013), and recent research suggests that general language relates to early numeracy, with specific math language mediating this relationship (Toll, 2013). Finally, *visuospatial abilities* support many mathematical competences (Geary, 2004). One of those is the domain of *time-related competences* (Burny, Valcke, & Desoete, 2009; Eden, Wood, & Stein, 2003; Freedman, Leach, & Kaplan, 1994), which includes the abilities associated with measuring or recording time and incorporates aspects such as clock reading, calendar use, and measuring of time intervals (Burny et al., 2009).

Most studies on mathematical abilities of children with ASD only use a global composite score, failing to account for the componential nature of mathematics. As such, few hypotheses can be formulated regarding the performance of children with ASD on these different domains of mathematics. The procedural calculation and number fact retrieval abilities, sometimes termed calculation, computation, or numerical operations, have been characterized from lower (Wei, Lenz, & Blackorby, 2013) to average (Minshew, Goldstein, Taylor, & Siegel, 1994; Titeca et al., 2014) or even better (Iuculano et al., 2014; Titeca et al., 2014) than those of TD children. Word/language problems, also termed applied problems, have been reported as a weaker (Minshew et al., 1994), average (Iuculano et al., 2014) or higher (Titeca et al., 2014) domain of mathematics compared to TD children. Finally, only one study looked into the time-related competences of children with ASD, reporting average performance in high-functioning children with ASD when compared to TD peers (Titeca et al., 2014).

Objectives and research questions

The present study aimed at examining whether grade 1 to 4 high-functioning elementary school children with ASD scored significantly different from age-adequate norms on four domains of mathematics: procedural calculation, number fact retrieval, word/language problems, and time-related competences. As such, a between-group perspective was taken to investigate the mathematical abilities of children with ASD. Because we observe a discrepancy between clinical reports and a limited number of studies, it is difficult to generate any hypotheses. Whereas the mathematics performance of children with ASD imposes a matter of significant concern to teachers and therapists (Department for Education and Skills, 2001; van Luit et al., 2006), between-group studies comparing mathematics performance in children with ASD and TD peers generally report average to enhanced scores (e.g., Chiang & Lin, 2007; Church, Alisanski, & Amanullah, 2000; Iuculano et al., 2014). Moreover, little (and inconsistent) evidence is available on the performance of children with ASD regarding the distinct domains of mathematics. As such, we wanted to contribute to a more balanced picture of the possible strengths and weaknesses of children with ASD in the field of mathematics when comparing them to TD peers.

METHOD

Participants and procedure

The study included 31 first graders (24 boys), 27 second graders (23 boys), 39 third graders (32 boys), and 24 fourth graders (22 boys). The mean age of the children was 7.79 years (*SD* = 1.08). All children previously received a formal diagnosis of ASD made independently by a qualified multidisciplinary team according to the criteria of the *Diagnostic and Statistical Manual of Mental Disorders, 4th edition, Text Revision* (APA, 2000). This formal diagnosis was confirmed by a score above the ASD cut-off (*T*-score > 60) on the Dutch version of the *Social Responsiveness Scale* (*SRS*; Roeyers, Thys, Druart, De Schryver, & Schittekatte, 2011). All children were recruited through integrated educational services (Geïntegreerd ONderwijs [GON]; Flemish Ministry of Education and Training, 2013b), which provide individual support and coaching to children with developmental, learning, or educational disabilities who attend general education classrooms. Ten out of 14 services that were contacted agreed to participate. In total, 375 children were addressed and the study had a response rate of 50,67% (*n* = 190). Of these 190 children, 121 met inclusion criteria.

GON counselors were asked to provide IQ records of all pupils. Children were only included in the study if they were considered to be at least of average intelligence, either by displaying a full scale IQ (FSIQ) score above 80 (n = 101) or – if no exact figures were available – by clinically reported capacities of average intelligence (n = 20). The *Hollingshead Four Factor Index* score (Hollingshead, 1975) was calculated as a measure of socioeconomic status (SES), taking into account parents' education, occupation, marital status, and sex. Table 1 provides an overview of the sample characteristics by grade level.

Table 1. *Descriptive characteristics of the sample*

	M	*(SD)*	Kruskal Wallis test
Age			$\chi^2(3) = 111.72$, $p < .001$
Grade 1 (n = 31)	6.35	(0.24)	
Grade 2 (n = 27)	7.38	(0.26)	
Grade 3 (n = 39)	8.28	(0.31)	
Grade 4 (n = 24)	9.28	(0.30)	
FSIQ[a]			$\chi^2(3) = 1.80$, $p = .616$
Grade 1 (n = 27)	102.67	(12.31)	
Grade 2 (n = 21)	104.19	(15.41)	
Grade 3 (n = 32)	107.16	(13.80)	
Grade 4 (n = 21)	105.62	(13.57)	
SES[b]			$\chi^2(3) = 3.47$, $p = .325$
Grade 1 (n = 31)	40.29	(12.12)	
Grade 2 (n = 27)	40.91	(13.03)	
Grade 3 (n = 38)	44.38	(11.76)	
Grade 4 (n = 24)	43.85	(11.55)	
SRS[c]			$\chi^2(3) = 7.29$, $p = .063$
Grade 1 (n = 31)	84.23	(18.54)	
Grade 2 (n = 27)	86.07	(17.95)	
Grade 3 (n = 39)	88.46	(16.80)	
Grade 4 (n = 24)	95.04	(15.97)	

Note. Nonparametric analyses were conducted, because assumptions of normality were violated; [a]Full Scale IQ, [b]Socioeconomic status, [c]*T*-score on *Social Responsiveness Scale*.

Mean scores on FSIQ and SES of the four grades did not differ significantly. However, there was a trend for a difference in the severity of autism spectrum symptoms, with children in grade 4 displaying a higher level of impairments in social responsiveness than the younger children (see Table 1).

The participants were tested individually by their own GON counselor during the period of November 2012 till January 2013. All GON counselors were trained in small groups during a two-hour workshop to insure a standardized assessment of the tasks. In this workshop, the test materials and procedure were demonstrated and discussed. A follow-up contact was organized to address any additional questions afterwards. The test battery took approximately one hour and a half to administer. The assessment was spread over different test sessions so as to fit within the duration of a counseling moment (50 minutes). Parental consent forms were obtained and the study protocol was approved by the ethical committee of the Faculty of Psychology and Educational Sciences at Ghent University.

Materials

Procedural calculation and word/language problems. The procedural calculation abilities as well as the word/language problem abilities of the children were tested using subtests of the *Cognitive Developmental Skills in Arithmetics* (*Cognitieve Deelhandelingen van het Rekenen* [*CDR*]; Desoete & Roeyers, 2006). All children completed the procedural subtest (including number splitting and addition/subtraction by regrouping exercises, presented in a number problem format; e.g., “12 – 9 = __”; *P*); the linguistic subtest (one-sentence word problems; e.g. “1 more than 5 is__”; *L*); the mental representation subtest (one-sentence mathematical problems that go beyond a superficial approach of keywords and that require a mental representation to prevent number crunching errors such as answering “38” on the question “47 is 9 less than __”; *M*); and the contextual subtest (more-than-one-sentence word problems; e.g. “Wanda has 47 cards. Willy has 9 cards less than Wanda. How many cards does Willy have?”; *C*). As such, we could differentiate between simplicity (*L*) versus complexity (*C*) and tasks with (*M*) versus without (*L*) mental representation involved. In the current study, the test versions of grade 1-2 and grade 3-4 of the *CDR* were used. Cronbach’s alphas were

.93 and .91 for first and second grade respectively, and .89 for both third and fourth grade (Desoete & Roeyers, 2006).

Number fact retrieval. The *Arithmetic Number Facts Test* (*Tempotest Rekenen* [*TTR*]; De Vos, 1992) is a numerical facility test assessing the memorization and automatization of arithmetic facts. The *TTR* consists of five subtests: addition, subtraction, multiplication, division, and mixed exercises. Participants were instructed to solve as many items as possible in five minutes; they could work one minute on every subtest. In first and second grade, the assessment was limited to the addition and subtraction exercises, as multiplications and divisions are only practiced and mastered at the end of second grade. De *TTR* demonstrated good psychometric values in a study of 395 second graders with a Cronbach's alpha of .90 (Desoete, Ceulemans, De Weerdt, & Pieters, 2012).

Time-related competences. *The Time Competence Test* (*TCT*; *Test Tijdscompetentie*; Burny, 2012; Burny, Valcke, & Desoete, 2012) is a test battery developed to assess the mastery of time-related competences in elementary school children. The test consists of four domains: clock reading, time intervals, time-related word problems, and calendar use. Cronbach's alphas were .76 for the first grade, .61 for second grade, .90 for third grade, and .88 for fourth grade (Burny, 2012).

Analyses

First, an explorative correlation analysis was conducted to assess the linear relationships between mathematics and some sample characteristics. Next, analyses were conducted to compare the performance of the ASD children to the scores of the normed population sample. In order to do so, z-scores using the mean and standard deviation of the normed samples of the tests were calculated for the respective measures. Graphical inspection of the data by grade revealed non-normal distributions for most of the variables. Hence, nonparametric tests were used for evaluation. In a first step, an overall independent samples median test was used to determine if any of the median z-scores for the four grades was statistically different from zero or not. This was done both for a general math index (based on the average z-score of all four domains of mathematics) and for the four domains of mathematics separately. In case a significant overall effect was found (for the general math index or for a particular domain of mathematics), a Wilcoxon signed rank test was conducted to determine in which of the four grades the performance differed significantly from zero. To control the overall type 1-error, a Bonferroni correction was applied for each of the four grades (i.e., *p*-values were assessed at the .013 level). Finally, the data were plotted to examine for possible subgroups or outliers in the ASD group. All analyses were performed in SPSS Version 21.0 (IBM Corp., 2012).

RESULTS

Bivariate relations among the constructs

Table 2 provides the correlations between the domains of mathematics and some sample characteristics.

Table 2. *Correlations between domains of mathematics and sample characteristics*

	PC[a]	WLP[b]			NFR[f]	TRC[g]	SES[h]	FSIQ[i]
		L[c]	*M*[d]	*C*[e]				
PC[a]	-							
WLP[b]	**							
L-tasks[c]	.25**	-						
M-tasks[d]	.27**	.40**	-					
C-tasks[e]	.51**	.45**	.51**	-				
NFR[f]	.51**	.19*	.18[t]	.35**	-			
TRC[g]	.35**	.25**	.34**	.42**	.31**	-		
SES[h]	.28**	.11	.14	.25**	.27**	.10	-	
FSIQ[i]	.40**	.31**	.50**	.42**	.15	.25*	.19[t]	-
SRS[j]	.06	-.10	-.01	.07	-.01	.04	.03	.03

Note. [t]$p < .100$, *$p < .050$, **Bonferroni-corrected ($p < .001$); [a]Procedural calculation, [b]Word/language problems, [c]Linguistic tasks, [d]Mental representation tasks, [e]Contextual tasks, [f]Number fact retrieval, [g]Time-related competences, [h]Socioeconomic status, [i]Full scale IQ, [j]Raw score on the *Social Responsiveness Scale*.

Correlations were (marginally) significant and varied from $\rho = .18$ to $\rho = .51$ between the four domains of mathematics, justifying the use of a general math index. No significant correlations were found between mathematics and the severity of autism spectrum symptoms.

General math index

An independent samples median test indicated that the median z-scores were not significantly different from zero in any of the four grades, $\chi^2(3) = 6.09$, $p = .107$ (see Figure 1). No further analyses for the separate grades seemed indicated.

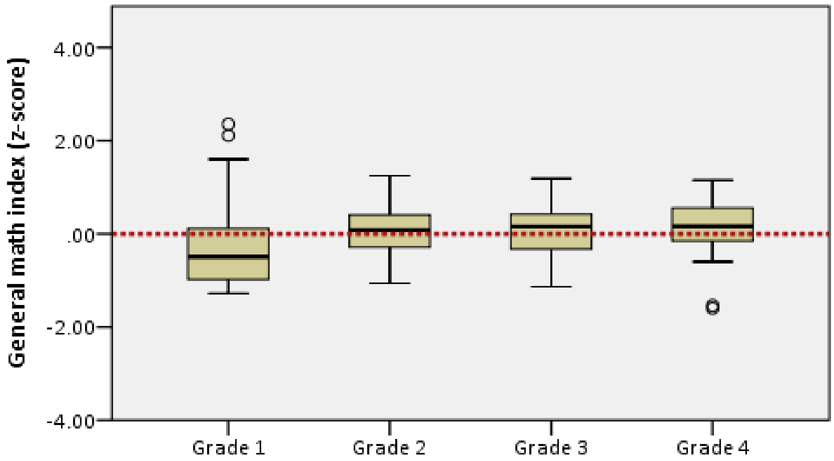

Figure 1. General math in elementary school children with autism spectrum disorder.

The plot of the general math index scores showed only few (1.65%) extreme scores (deviating more than two standard deviations from 0) and 82.64% of the scores were situated between one standard deviation below or above 0, suggesting that the results were comparable to the normed population (see Figure 2). Furthermore, the graph showed no indications for distinct subgroups of children balancing out opposite scores (Figure 2).

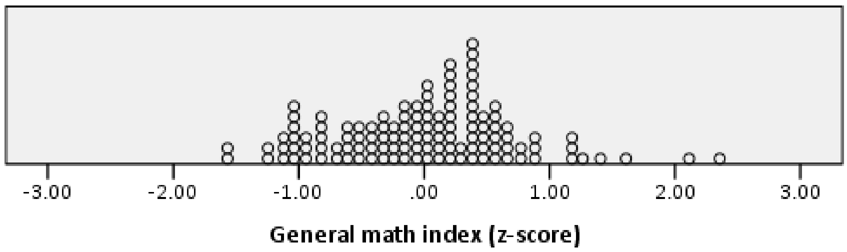

Figure 2. Dot plot of individual differences in general math of elementary school children with autism spectrum disorder.

Four domains of mathematics

An independent samples median test (repeated for all four domains of mathematics) was conducted to investigate whether at least one of the median z-scores of the four grades was significantly different from zero. This was the case in all domains of mathematics, except for number fact retrieval (see Table 3). Nevertheless, Figure 3 illustrates the performance per grade for all domains of mathematics.

Table 3. *Descriptives of the different domains of mathematics*

	M	*(SD)*	Independent samples median test
Procedural calculation	-0.02	(0.95)	$\chi^2(3) = 20.58$, $p < .001$
Word/language problems			
L-tasks[a]	0.33	(0.99)	$\chi^2(3) = 9.36$, $p = .025$
M-tasks[b]	0.03	(1.22)	$\chi^2(3) = 10.96$, $p = .012$
C-tasks[c]	0.17	(0.95)	$\chi^2(3) = 17.49$, $p = .001$
Number fact retrieval	-0.04	(1.04)	$\chi^2(3) = 3.16$, $p = .367$
Time-related competences	-0.45	(0.92)	$\chi^2(3) = 9.78$, $p = .021$

Note. [a]Linguistic tasks, [b]Mental representation tasks, [c]Contextual tasks.

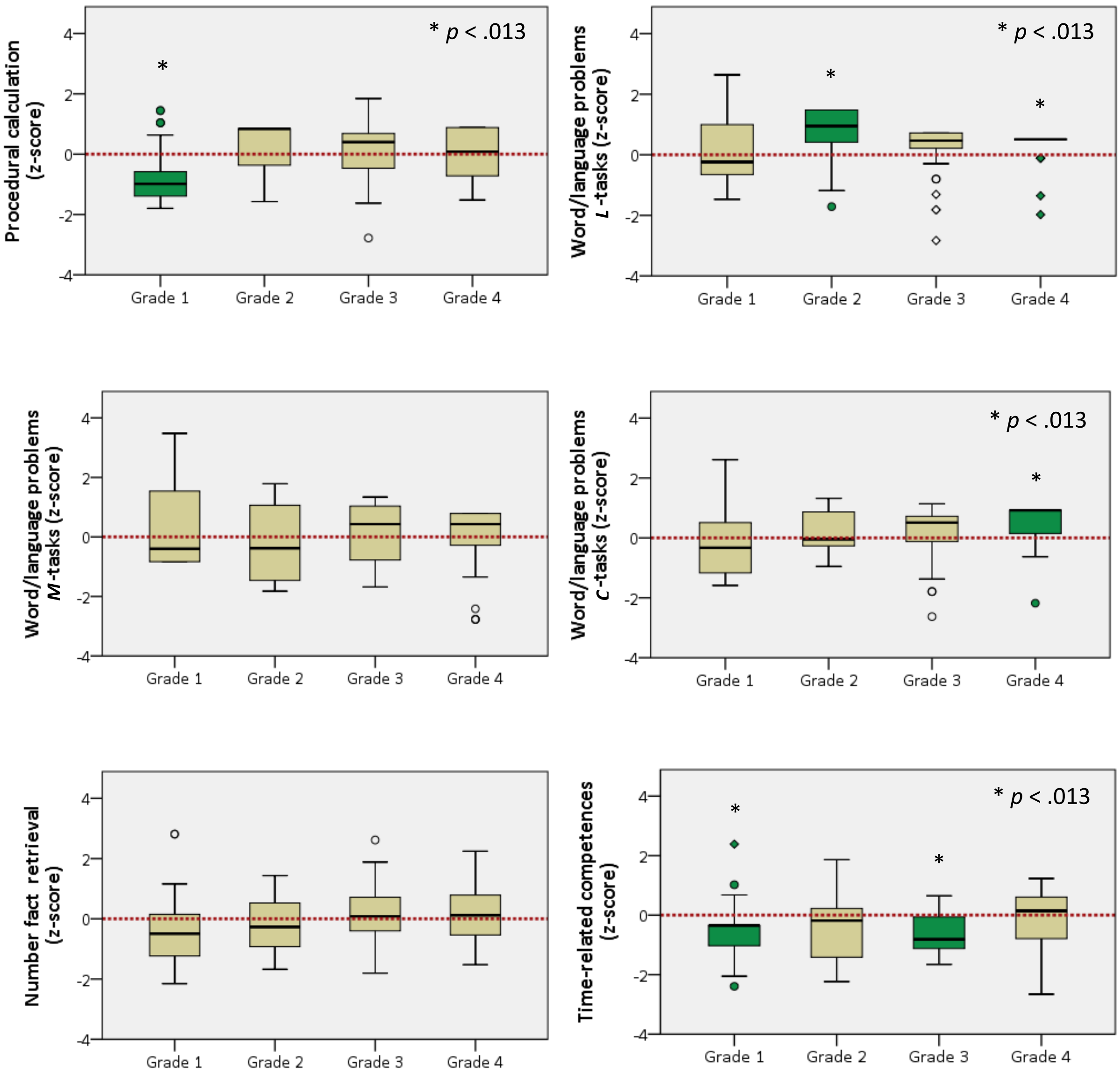

Figure 3. Performance of elementary school children with autism spectrum disorder on the different domains of mathematics.

For the domains in which a significant difference was found, Wilcoxon signed rank tests were executed per grade to reveal in which grades the median z-score deviated significantly from zero. For procedural calculation, children with ASD in the first grade scored significantly below average, *Mdn* = -0.98, $z = -2.60$, $p = .009$, $r = -.47$, whereas no significant (Bonferroni-adjusted) differences could be found in the other grades. For word/language problems, no significant differences could be found in first and third grade. In contrast, children with ASD scored significantly above average on *L*-tasks in second grade, *Mdn* = 0.95, *z* = 3.06, *p* = .002, *r* = .59, and above average on *L*-tasks and *C*-tasks in fourth grade, *Mdn* = 0.51, *z* = 2.95, *p* = .003, *r* = .60 and *Mdn* = 0.92, *z* = 3.27, *p* = .001, *r* = .67 respectively. For time-related competences, children with ASD scored significantly below average in first grade, *Mdn* = -0.35, *z* = -3.42, *p* = .001, *r* = -0.63, and in third grade, *Mdn* = -0.81, *z* = -4.26, *p* < .001, *r* = -0.69.

Finally, an in-depth analysis of individual differences on the separate mathematical domains showed plots that were highly similar to those of the general math index scores, indicating only few extreme scores and no indications of averaging out through subgroups of children.

Discussion

This study aimed at comparing the performance on procedural calculation, number fact retrieval, word/language problems, and time-related competences of grade 1 to 4 elementary school children with ASD to the scores of the normed population. General findings, limitations, and implications of the study are provided below.

General findings

First, small to large (marginally) significant correlations were found between the different domains of mathematics (Cohen, 1988), meaning that all domains relate – in a greater or lesser extent – to each other. Although this finding makes analyses with a general math index possible, it is still warranted to consider the various mathematical domains separately (Dowker, 2008), as it gives rise to a more fine-tuned image of the mathematical abilities of individuals with ASD (cf. infra). In contrast, no significant correlations were found between mathematics and the severity of autism spectrum symptoms (in the domain of social responsivity) in our homogeneous group of average intelligent GON children. This replicates previous findings (Jones et al., 2009).

Second, children with ASD showed a poor start in procedural calculation in first grade, but seemed to be able to regain the lost ground in the next grades. The suggestion (as the data are only cross-sectional in nature) of an evolution in performance might help to put the results of previous studies in a more developmental perspective. Our data suggest that the reported average or enhanced mathematical abilities of elementary school children with ASD in other studies (Chiang & Lin, 2007; Church et al., 2000; Iuculano et al., 2014) may not be present at the initial start of elementary school, but emerge perhaps only later on when children catch up.

Because procedural calculation exercises and number fact problems bear a close resemblance to each other (both are presented in a number problem format), the question may arise as to why children with ASD only show problems with the former ones in first grade. Number fact retrieval appeals to rote memory and is taught systematically and straightforward within the Flemish curriculum (Domahs & Delazer, 2005). In contrast, procedural calculation requires further computational strategies and processes to solve the exercise (Domahs & Delazer, 2005). As such, more intuitive or implicit knowledge – which is less systematically taught and rehearsed – is essential to execute procedural calculation tasks. For instance, one has to find out why splitting numbers is beneficial for solving addition or subtraction by regrouping exercises. In this regard, our findings align with previous studies reporting difficulties with the grasping of implicit rules and assumptions in children with ASD (Gordon & Stark, 2007; Klinger & Dawson, 2001; Klinger, Klinger, & Pohlig, 2007). However, not everyone agrees with this line of reasoning, because some studies report intact implicit learning abilities in children with ASD (Barnes et al., 2008; Brown, Aczel, Jimenez, Kaufman, & Grant, 2010; Kourkoulou, Leekam, & Findlay, 2012), or propose other mechanisms that may impact negatively on implicit learning without implicit learning itself being impaired (Brown et al., 2010). Moreover, it is important to be aware of the fact that implicit learning is often approached from a different angle in research (e.g., computerized tasks) than in real-world settings. Nevertheless, the distinction between intact mechanical learning (Goldstein, Minshew, & Siegel, 1994; Minshew et al., 1994) and difficulties with more complex implicit learning (Gordon & Stark, 2007; Klinger & Dawson, 2001; Klinger et al., 2007) in children with ASD might provide a possible explanation for our findings, and generate a hypothesis for future research to look further into.

Third, children with ASD showed age-adequate or superior performance on explicitly presented word/language problems, when formulated in short and clear sentences. Given the fact that at least a subgroup of children with ASD demonstrates impaired structural language abilities (Boucher, 2012; Rapin, Dunn, Allen, Stevens, & Fein, 2009), one could have expected a poorer performance on word/language problems in some children, given the close relationship between general language and specific math language (Toll, 2013). However, our results are in accordance with the previously reported intact abilities of children with ASD to solve word/language problems in the study of Iuculano et al. (2014). In addition, the results highlight the importance of making a distinction between different kinds of word/language problems. When formulating clear sentences (*L*-tasks), without redundant or irrelevant information, children with ASD might even excel in solving word/language problems when compared to TD peers, as our dataset revealed. This might even be the case for more complex multiple-sentences ones (*C*-tasks), whereas the scores on exercises requiring mental representation (*M*-tasks) were found to be within the average range. Future research should also include multiple-sentence word/language problems that require the use of mental representation, or word/language problems containing superfluous and irrelevant information. Since children with ASD are known to have foremost difficulties with complex processes (Goldstein et al., 1994; Minshew et al., 1994; Noens & van Berckelaer-Onnes, 2005), this higher complexity level may cause different results and give rise to a more fine-grained view on their word/language problem performance.

Fourth, both in first and third grade, children with ASD showed a below-average performance on the *TCT*. Time comprehension or clock reading is a complex matter that has proven to be difficult for all children (Burny et al., 2009; Monroe, Orme, & Erickson, 2002). However, due to its abstract and implicit nature and the absence of concrete representations (Foreman, Boyd-Davis, Moar, Korallo, & Chappell, 2008; Panagiotakopoulos & Ioannidis, 2002), it might even be more difficult for children with ASD to grasp our conventional time systems. The reason why the first and third grade might be particularly difficult, can perhaps be found in the Flemish math curriculum (Flemish Ministry of Education and Training, 2013a). In first grade, children get their first formal introduction in calendar use and clock reading, for which a new structured metric system has to be taught. Children learn to read the clock up until simple and half hour times. In second grade, children only learn to read quarter past or before times. In third grade, the digital format is introduced and children have to read the clock up until one minute precise, causing a large amount of new material to be presented at once. In the fourth grade, previous knowledge is rehearsed and further mastered. Children with ASD demonstrate difficulties with novelty processing and learning new or complex behaviors (Maes, Eling, Wezenberg, Vissers, & Kan, 2011; Minshew & Goldstein, 1998; Minshew et al., 1994), which may underlie the impoverished performances found in grade 1 and grade 3, as well as it may contribute to the weaker start in procedural calculation mentioned earlier.

Strengths and limitations

Because previous studies on mathematics in children with ASD are scarce and results are inconclusive, the current study offers a valuable contribution to this field. The focus on different domains of mathematics has proven to be a meaningful approach, as performance seems to depend on the specific abilities that are assessed. In addition, the current study gives an initial impetus to take a more developmental perspective when assessing mathematics in children with ASD. In line with Goldstein et al. (1994), we agree that academic functioning of children with ASD may largely depend on the age at which the ability is assessed. Furthermore, the inclusion of a quite large group of children who followed the standard educational curriculum made it possible to interpret the results of a comparison with the normed population more straightforward. Finally, all grades were comparable regarding FSIQ and SES. There was a trend toward a difference in autism symptom severity, but given the nonsignificant correlations with mathematics, this factor could also not provide an alternative explanation for the results.

However, the current findings should be placed in a context of some limitations, which can serve as a source of inspiration for future research. Although the results suggest a developmental evolution in for example procedural calculation, longitudinal research should be conducted to confirm the observed pattern. Next, although the examination of the plots of individual differences showed no indications of substantial bias caused by outliers or the presence of subgroups, future research with still larger groups is needed in order to make cluster analysis possible. In addition, complementing a between-group perspective with a within-group perspective (in which different areas of functioning can be contrasted and compared to each other) would be of added value when further exploring the mathematical abilities of children with ASD. Finally, due to our homogeneous sample of GON children of average intelligence, the conclusions of this study cannot simply be generalized to children in special educational settings or children of other intelligence levels.

Educational implications

Based on the findings of this study, some educational implications can be made regarding the mathematical trajectory of children with ASD in elementary school. First of all, for all four domains of mathematics that were assessed, children with ASD did not score significantly lower than age-adequate norms in grade 4. This suggests that, despite some difficulties in first and third grade, mathematics overall is not a persistent stumbling block for children with ASD. Therefore, it might not be indicated to implement general and large-scale interventions or adaptations to the currently used materials.

Although the findings of this study were not the result of the scores of two subgroups balancing each other out on average, still a large variation in scores was present. In this respect, children with ASD score as variable as TD children, making it impossible to provide a “prototypic” image of the math performance for all children with ASD. The current study supports the idea of making a thorough assessment of an individual’s strengths and weaknesses in order to stipulate appropriate educational guidelines. Based on this profile, one could build on strengths to urge improvement in other, more difficult, domains of mathematics (Jones et al., 2009).

Furthermore, our findings indicate that autism-specific information processing characteristics might influence mathematics performance. The fact that children with ASD performed weaker on procedural calculation in first grade and on time-related competences in first and third grade is in line with reports of difficulties with the introduction of new, implicit, or complex information (Courchesne, Lincoln, Kilman, & Galambos, 1985; Gomot & Wicker, 2012; Klinger et al., 2007; Maes et al., 2011; Minshew & Goldstein, 1998; Minshew et al., 1994). The fact that on group level, average to high scores were observed for word/language problems compared to the normed samples, might also be related to this aspect. All word/language problems were operationalized as relatively short, concise, and straightforward tasks. It is however possible that high-functioning children with ASD perform as well as TD peers, as long as the difficulty level does not exceed a certain threshold of complexity, a suggestion previously formulated by Goldstein et al. (1994).

Therefore, without the need of implementing extended large-scale interventions, still some propositions can be made to sustain a positive mathematical development in children with ASD. We recommend, for example, teachers and clinicians to be attentive for the possible impact of these autism-specific information processing characteristics. Children with ASD might in some cases need more time to process information and to deal with new or complex information (e.g., Happé, 1999; Minshew & Goldstein, 1998). It seems for example plausible that a more direct teaching approach is beneficial for children with ASD, an approach in which the underlying patterns of thought are addressed explicitly before the children understand the usefulness of certain strategies or procedures, or before they can apply the procedures correctly. When following the line of reasoning that other mechanisms impact negatively upon implicit learning, one could also try to pay attention to these factors, such as the overuse of explicit strategies, the attentional focus, or the offline learning and atypical consolidation of acquired knowledge (Brown et al., 2010).

Related to this, it will be important to not only focus on current outcomes, but also to closely monitor the learning process of an individual child on these domains. It can be helpful to keep track of the changing needs of a child, as well as to keep in mind the specific demands of the math curriculum. When doing so, it may in some cases be possible to judge beforehand when additional guidance will be needed. Revealing more closely the exact impact of these autism-specific information processing characteristics on math performance is therefore a promising path for future research to take.

To summarize, elementary school children with ASD show a profile of strengths, average abilities, and weaknesses in mathematics. Based on our findings, it is recommended that future research takes into account several domains of mathematics. Furthermore, one should be aware of the autism-specific information processing difficulties that might influence academic functioning when further exploring this topic. Finally, it will be important to look at individual strengths and weaknesses when following up the mathematical trajectory of children with ASD.

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CHAPTER 5

PRESCHOOL PREDICTORS OF MATHEMATICS IN FIRST GRADE CHILDREN WITH AUTISM SPECTRUM DISORDER[1]

ABSTRACT

Up till now, research evidence on the mathematical abilities of children with autism spectrum disorder (ASD) has been scarce and provided mixed results. The current study examined the predictive value of five early numerical competencies for four domains of mathematics in first grade. Thirty-three high-functioning children with ASD were followed up from preschool to first grade and compared with 54 typically developing children, as well as with normed samples in first grade. Five early numerical competencies were tested in preschool (5-6 years): verbal subitizing, counting, magnitude comparison, estimation, and arithmetic operations. Four domains of mathematics were used as outcome variables in first grade (6-7 years): procedural calculation, number fact retrieval, word/language problems, and time-related competences. Children with ASD showed similar early numerical competencies at preschool age as typically developing (TD) children. Moreover, they scored average on number fact retrieval and time-related competences, and higher on procedural calculation and word/language problems compared to the normed population in first grade. When predicting first grade mathematics performance in children with ASD, both verbal subitizing and counting seemed to be important to evaluate at preschool age. Verbal subitizing had a higher predictive value in children with ASD than in TD children. Whereas verbal subitizing was predictive for procedural calculation, number fact retrieval, and word/language problems, counting was predictive for procedural calculation and, to a lesser extent, number fact retrieval. Implications and directions for future research are discussed.

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[1] Based on Titeca, D., Roeyers, H., Josephy, H., Ceulemans, A., & Desoete, A. (2014). Preschool predictors of mathematics in first grade children with autism spectrum disorder. *Research in Developmental Disabilities*. http://dx.doi.org/10.1016/j.ridd.2014.07.012

INTRODUCTION

Autism spectrum disorders (*ASD*) are characterized by persistent deficits in social communication and social interaction, together with restrictive, repetitive patterns of behavior, interests, or activities (American Psychiatric Association [APA], 2013). Despite the predominant clinical focus on the social-communicative impairments in children with ASD, interest in the academic functioning of these children has grown more recently (Tincani, 2007; Whitby & Mancil, 2009). Indeed, when tackling the issue of educational inclusion of children with ASD, it is important to gain insight into their academic strengths or needs. Even though a large part of children with ASD are defined as high-functioning (i.e., displaying an IQ score of at least 70), appropriate support or accommodation might still be needed to reach their full potential (Whitby & Mancil, 2009). Regarding the field of mathematics, teachers and therapists often consider mathematics as one of the difficult subject matters for children with ASD (Department for Education and Skills, 2001; van Luit, Caspers, & Karelse, 2006). However, the amount of research on this topic does not match their concern. Not only are studies on mathematics in children with ASD scarce, the few existing studies also focus on different aspects of the topic: mathematical processes (e.g., Gagnon, Mottron, Bherer, & Joanette, 2004) versus mathematical outcomes (e.g., Chiang & Lin, 2007); or within-group (mathematical abilities relative to own cognitive abilities; e.g., Mayes & Calhoun, 2003) versus between-group (mathematical abilities of children with ASD compared with typically developing (TD) children; e.g., Iuculano et al., 2014) analyses or comorbidity studies (e.g., Mayes & Calhoun, 2006). When consulting existing literature, two opposite views emerge. First of all, anecdotal and descriptive research (Baron-Cohen, Wheelwright, Burtenshaw, & Hobson, 2007; Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001; Sacks, 1986) as well as some empirical studies (Iuculano et al., 2014; Jones et al., 2009) have put forward that children with ASD show average or enhanced mathematical abilities compared to their TD peers. In contrast, other empirical studies such as comorbidity studies (Mayes & Calhoun, 2006; Reitzel & Szatmari, 2003) and some within-group studies (Chiang & Lin, 2007; Mayes & Calhoun, 2003) suggest mathematical problems in children with ASD.

A limitation of the aforementioned research is the cross-sectional nature of these studies (e.g., Iuculano et al., 2014; Jones et al., 2009; Mayes & Calhoun, 2003). Recently, a longitudinal study examined the reading and mathematics profiles and their growth trajectories in children with ASD (Wei, Christiano, Yu, Wagner, & Spiker, 2014). However, despite the identification of several *early numerical competencies* of preschoolers as strong predictors of later mathematical abilities (e.g., DiPema, Lei, & Reid, 2007; Duncan et al., 2007; Kroesbergen, van Luit, & Aunio, 2012; Locuniak & Jordan, 2008), the predictive value of such early numerical competencies for later mathematical abilities in children with ASD remains undisclosed as yet.

The importance of early numerical competencies for later mathematics

N. C. Jordan and Levine (2009) identified five early numerical competencies, namely verbal subitizing, counting, magnitude comparison, estimation, and arithmetic operations. *Verbal subitizing* can be described as the rapid (40-100 ms/item), automatic, and accurate enumeration of small quantities of up to three (or four) items (Kaufman, Lord, Reese, & Volkmann, 1949). Several studies demonstrated that subitizing is an important factor in mathematical development (Landerl, Bevan, & Butterworth, 2004; Penner-Wilger et al., 2007; Träff, 2013), and longitudinal research demonstrated that subitizing is a domain-specific predictor for later mathematical performance over and above domain-general abilities (Krajewski & Schneider, 2009; Kroesbergen, van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; LeFevre et al., 2010; Reigosa-Crespo et al., 2012). *Counting* has also proven to be of central influence for the development of adequate mathematical abilities (Aunola, Leskinen, Lerkkanen, & Nurmi, 2004; Fuson, 1988; Le Corre, Van de Walle, Brannon, & Carey, 2006; Passolunghi, Vercelloni, & Schadee, 2007; Wynn, 1990). Whereas procedural counting knowledge (the ability to perform a counting task) has proven to be predictive for numerical facility, conceptual counting knowledge (the understanding of why a procedure works or is legitimate) is predictive for untimed mathematical achievement (Desoete, Stock, Schepens, Baeyens, & Roeyers, 2009; LeFevre et al., 2006). *Magnitude comparison* is the ability to discriminate two quantities in order to point out the largest of both (Gersten et al., 2012). Although number comparison has proven to play an important role in the development of mathematical abilities (De Smedt, Verschaffel, & Ghesquiere, 2009; Holloway & Ansari, 2009; N. C. Jordan, Glutting, & Ramineni, 2010), there is still debate on whether nonsymbolic number comparison as well as symbolic number comparison performance relates to later mathematics. Whereas some researchers state it does (Halberda, Mazzocco, & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2013; Mazzocco, Feigenson, & Halberda, 2011), others acknowledge only the contribution of symbolic number comparison (Bartelet, Vaessen, Blomert, & Ansari, 2014; Holloway & Ansari, 2009; Sasanguie, De Smedt, Defever, & Reynvoet, 2012; Sasanguie, Gobel, Moll, Smets, & Reynvoet, 2013). *Estimation* is often assessed using a number line task (Booth & Siegler, 2006; Siegler & Booth, 2004; Siegler & Opfer, 2003). Several studies indicated that the linearity of number line judgments is positively correlated with math achievement scores (Ashcraft & Moore, 2012; Siegler & Booth, 2004). Moreover, estimation accuracy (measured with mean percentages of absolute error [PAE] on the number line estimation task) has proven to be a unique predictor of mathematical achievement later on, next to the predictive role of linearity (Sasanguie et al., 2012; Sasanguie et al., 2013). Finally, *arithmetic operations* involve the ability to perform basic addition and subtraction transformation exercises (Purpura & Lonigan, 2013). Arithmetic operations, as part of a larger early numerical competencies battery, have proven to be predictive for later mathematical abilities, especially for applied problem solving (N. C. Jordan et al., 2010).

This short overview demonstrates that early numerical competencies are the first mathematical building blocks on which later mathematics is built (Berch, 2005; Geary, 2000; N. C. Jordan et al., 2010). However, two remarks should be made. On the one hand, a lot of studies incorporate only one of the early numerical competencies, relating it to one outcome score for mathematics (e.g., De Smedt et al., 2009; LeFevre et al., 2006; Siegler & Booth, 2004). On the other hand, many studies combine domain-specific and domain-general factors in one study, investigating the relative contribution of these categories without making a distinction between numerical competencies (N. C. Jordan, Kaplan, Locuniak, & Ramineni, 2007; Passolunghi & Lanfranchi, 2012; Träff, 2013). Moreover, in studies making this distinction, different early competencies are suggested as strong(est) predictors: counting and logical abilities (e.g., Stock, Desoete, & Roeyers, 2010); counting, verbal subitizing, and magnitude comparison (Praet, Titeca, Ceulemans, & Desoete, 2013); or arithmetic operations (operationalized through number combinations and story problems; N. C. Jordan, Kaplan, Ramineni, & Locuniak, 2009). As such, it remains an unresolved question which of the early numerical competencies are most strongly associated with *mathematical abilities* in elementary school (Praet et al., 2013; Stock et al., 2010).

Mathematical abilities in elementary school children

Although there is no unitary mathematical construct in elementary school (Dowker, 2005; J. A. Jordan, Mulhern, & Wylie, 2009), several vital subcomponents are involved in adequate mathematical development. Children who are struggling with these mathematical components show difficulties in mathematics, which can manifest themselves on four domains: number sense, number facts, calculation, or mathematical reasoning (APA, 2013). Whereas *number sense* can be considered as a low-level construct that is already present before formal schooling (Dehaene, 2001), the other three domains reflect higher order or secondary abilities acquired through formal schooling (Geary, 2000). Dowker (2005) stated that *procedural calculation* is needed to solve arithmetic problems, converting numerical information into mathematical equations and algorithms. By executing arithmetic problems repetitively, basic number facts are retained in long-term memory and automatically retrieved if needed, termed as *number fact retrieval* (Dowker, 2005). Because some children might have problems in the area of procedural calculation whereas others have problems with automaticity and numerical facility (N. C. Jordan, Levine, & Huttenlocher, 1995), it is important to include both aspects in mathematics assessment. The domain of *mathematical reasoning* is associated with verbal problem-solving abilities (Geary, Saults, Liu, & Hoard, 2000; Meyer, Salimpoor, Wu, Geary, & Menon, 2010). Over time, word problems or contextual problems have gained importance in the mathematics curriculum (Kilpatrick, Swafford, & Findell, 2001). Likewise, the role of language in mathematics was investigated more extensively (Hickendorff, 2013; Negen & Sarnecka, 2012; Praet et al., 2013). Recent research suggests that general language relates to early numeracy and that specific math language mediates this relationship (Toll, 2013), therefore suggesting the importance of assessing *word/language problems* next to number facts and calculation. Finally, *time-related competences* are defined as the abilities associated with measuring or recording time and incorporate aspects such as clock reading, calendar use, and measuring of time intervals (Burny, Valcke, & Desoete, 2009). The concept of time is a complex construct, making it difficult to grasp by many children (Andersson, 2008; Burny et al., 2009). Given the particular difficulties of children with a *mathematical learning disorder* (*MLD*) on this domain (Burny, Valcke, & Desoete, 2012), it should also be included when assessing mathematical abilities in elementary school.

Regarding the predictive value of preschool competencies for these mathematical outcomes in elementary school, it was not until recently that there is a growing emphasis on the use of a multicomponential approach in mathematics research in general (Aunio & Niemivirta, 2010; J. A. Jordan et al., 2009). As such, only few studies have focused on different subcomponents or domains of mathematics as described above. The most investigated domains include number fact retrieval, calculation, and applied problems (e.g., N. C. Jordan et al., 2009; Stock et al., 2010).

Most studies on mathematical abilities of children with ASD also fail to account for the componential nature of mathematics, providing only a single component score. The study of Iuculano et al. (2014) is the only one to conclude that children with ASD show a cognitive strength on numerical operations, while scoring in the average range for mathematical reasoning. Jones et al. (2009) assessed the same two components of mathematics in children with ASD. However, their conclusions (16.2% of the cases had a relative strength and 6.1% had a relative weakness in mathematics) were only based on the numerical operations subscale, as these authors wanted to assess arithmetic ability, presumed to be the most elementary form of mathematics and to be measured by the numerical operations subscale.

Objectives and research questions

Surprisingly few studies have been conducted to explore the combined effect of early numerical competencies in preschool on mathematics performance in first grade (Praet et al., 2013). The present study addressed this gap by investigating five early numerical competencies (verbal subitizing, counting, magnitude comparison, estimation, and arithmetic operations) as predictors of four domains of mathematics in first grade (procedural calculation, number fact retrieval, word/language problems, and time-related competences) in TD children and children with ASD. Although in TD children there is evidence for the predictive value of these early numerical competencies for later mathematics performance, there is little empirical longitudinal research tapping the relationship between all these numerical competencies simultaneously on the one hand and first grade mathematics on the other hand.

More specifically, the current study addressed three major research objectives. The first aim of the study was to compare children with ASD and TD children on early numerical competencies (preschool) and on the domains of mathematics (first grade). Given the scarce and inconsistent results from previous studies, no specific hypotheses were postulated. The second aim of the study was to investigate the predictive value of the early numerical competencies for mathematics in first grade. Based on previous literature, one would expect to find all five numerical competencies to be predictive for mathematics performance one year later. It is, however, unclear which of the competencies would be most predictive. Moreover, within this second research aim, the predictive value toward the different domains of mathematics was investigated more in detail. The third aim of the study was to investigate whether the results of children with ASD were similar to the pattern found in TD children. With no previous literature available on this topic, this study wanted to provide the first exploratory analysis of the predictive value of five early numerical competencies in children with ASD.

METHOD

Participants and procedure

Eighty-seven children (58 boys, 29 girls) were followed up from preschool to first grade. The early numerical competencies were assessed in the final year of preschool (mean age = 5.97, *SD* = 0.43), whereas the four domains of mathematics were assessed in first grade (mean age = 6.72, *SD* = 0.34).

Children with ASD (27 boys, 6 girls) were recruited through rehabilitation centers, special school services, and other specialized agencies for developmental disorders. They had a formal diagnosis made independently by a qualified multidisciplinary team according to established criteria, such as specified in the *Diagnostic and Statistical Manual of Mental Disorders, 4th edition, Text Revision* (APA, 2000). For all children, this formal diagnosis was confirmed by a score above the ASD cut-off on the Dutch version of the *Social Responsiveness Scale* (*SRS*; Roeyers, Thys, Druart, De Schryver, & Schittekatte, 2011). The Dutch version of the *SRS* has a good internal consistency, with a Cronbach's alpha of .94 for boys and .92 for girls (Roeyers et al., 2011). Scores on the *Autism Diagnostic Observation Schedule* (*ADOS*; Lord et al., 2000) were available for 21 children with ASD. Children with and without *ADOS* scores did not differ significantly on the *SRS,* U = 91.00, p = .200[2]. In TD children (31 boys, 23 girls), there was no parental concern on developmental problems and all children scored below the ASD cut-off on the *SRS* (Roeyers et al., 2011).

Each participant had a full scale IQ (FSIQ) of 80 or more, measured with the *Wechsler Preschool and Primary Scale of Intelligence – Third edition* (*WPPSI-III*; Wechsler, 2002). As such, the study focused on a group of high-functioning children with ASD. Table 1 provides an overview of the sample characteristics.

Table 1. *Descriptive characteristics of the sample*

	TD (n = 54)		ASD (n = 33)			
	M	*(SD)*	*M*	*(SD)*	T-test	
Age T1 (in years)	5.79	(0.35)	6.27	(0.38)	t(85) = -5.96,	p < .001
Age T2 (in years)	6.63	(0.34)	6.87	(0.29)	t(85) = -3.32,	p = .001
FSIQ[a]	111.44	(11.93)	105.38	(13.27)	t(84) = 2.19,	p = .032
VIQ[b]	112.26	(11.32)	105.09	(13.50)	t(84) = 2.64,	p = .010
PIQ[c]	107.15	(11.79)	106.06	(15.07)	t(84) = 0.37,	p = .711
SES[d]	50.47	(7.49)	47.03	(9.05)	t(85) = 1.92,	p = .058
SRS (*T*-score)[e]	47.89	(5.56)	85.79	(19.10)	t(35.35) = -11.12,	p < .001

Note. TD = typically developing children, ASD = children with autism spectrum disorder;
[a]Full Scale IQ, measured with *Wechsler Preschool and Primary Scale of Intelligence – Third edition*, [b]Verbal IQ, [c]Performance IQ, [d]Socioeconomic status, measured with the *Hollingshead Four Factor Index* (Hollingshead, 1975), [e]*T*-score on *Social Responsiveness Scale*.

[2] A nonparametric analysis was conducted due to the sample sizes of the two groups and because the assumption of normality was violated.

Measures

Early numerical competencies in preschool.

Verbal subitizing. All children were tested with a computerized enumeration task (see Ceulemans et al., 2014; Praet et al., 2013 for further details), similar to the one described by Fischer, Gebhardt, and Hartnegg (2008) and based on the stimuli of Maloney, Risko, Ansari, and Fugelsang (2010). Participants saw one to nine black square boxes and were instructed to say aloud the number of squares as quickly and accurately as possible. The individual area, total area, and density of the squares were varied to insure that participants could not use non-numerical cues to make a correct decision (see Dehaene, Izard, & Piazza, 2005; Maloney et al., 2010). There were 15 practice trials and a test phase, which consisted of 72 samples (each numerosity was presented eight times) with a presentation time of 120 ms, a mask of 100 ms, and a total response time of 4,000 ms. This short presentation time prevented children from counting the squares (see Fischer et al., 2008). Cronbach's alpha was .88 for the subitizing range (1-3), .84 for the counting range (4-9), and .88 for the total range (1-9). The score on verbal subitizing was defined as the total accuracy score (% correct trials).

Counting. Counting was assessed using two subtests of the *Test for the Diagnosis of Mathematical Competencies* (*TEDI-MATH*; Grégoire, Noël, & Van Nieuwenhoven, 2004). The *TEDI-MATH* has proven to be conceptually accurate and clinically relevant and its predictive value has been demonstrated in several studies (e.g., Desoete et al., 2009; Stock, Desoete, & Roeyers, 2007). The procedural counting knowledge (subtest 1) was assessed using accuracy in counting row and counting forward to an upper bound and/or from a lower bound. The task had a maximum raw score of 8. The conceptual counting knowledge (subtest 2) was assessed by judging the validity of counting procedures based on the five basic counting principles formulated by Gelman and Galistel (1978). Children had to count both linear and nonlinear patterns of objects, and were asked some questions about it (e.g., "How many objects are there in total?"). Furthermore, they had to construct two numerically equivalent amounts of objects and use counting as a problem-solving strategy in a riddle. The maximum total raw score for this subtest was 13. The values for Cronbach's alpha ranged from .73 (procedural counting knowledge) to .85 (conceptual counting knowledge). The score on counting was defined as the total accuracy score (% correct items).

Magnitude comparison. A computerized magnitude comparison task (see Praet et al., 2013 for further details) was used in line with Halberda and Feigenson (2008) and Inglis, Attridge, Batchelor, and Gilmore (2011). In this task, two displays of black dots were presented simultaneously and participants were instructed to press the sun- (leftmost) or the moon- (rightmost) button corresponding to the largest numerosity on a five-button response box as quickly and accurately as possible. Six different ratios were presented. When dividing the smallest by the largest numerosity, these ratios were: .33, .50, .67, .75, .80, and .83. The individual area, total area, and density of the squares were varied to insure that participants could not use non-numerical cues to make a decision (see Dehaene et al., 2005). There were 15 practice trials and a test phase, which consisted of 72 samples (each ratio was presented twelve times) with a presentation time of 1,200 ms, a mask of 2,800 ms, and a total response time of 4,000 ms. Cronbach's alpha was .80 for the total task. The score on magnitude comparison was defined as the total accuracy score (% correct trials).

Estimation. A number line estimation task with a 0-100 interval was used, based on the procedure of Siegler and Opfer (2003). The task included 3 practice trials and 30 test trials. Stimuli were presented in a visual Arabic format (e.g., anchors 0 and 100, target number 3), an auditory-verbal format (e.g., anchors zero and hundred, target number three), and an analog magnitude format (e.g., anchors of zero dots and hundred dots, target number three dots). The dot patterns consisted of black dots in a white disc, controlled for perceptual variables using the procedure of Dehaene et al. (2005). Ten target numbers were selected: 2, 3, 4, 6, 18, 25, 42, 67, 71, and 86 (corresponding to sets A and B in Siegler & Opfer, 2003). Children were asked to put a single mark on the line to indicate the location of the number. Although the instructions could be rephrased if needed, no feedback was given to participants regarding the accuracy of their marks. The PAE was calculated per child as a measure of children's estimation accuracy, following the formula of Siegler and Booth (2004). Cronbach's alpha was .87 for the total task. The score on estimation was defined as the total PAE.

Arithmetic operations. Arithmetic operations were assessed using subtest 5.1 of the *TEDI-MATH* (Grégoire et al., 2004). A series of six visually supported addition and subtraction exercises was presented to the children (e.g., "Here you can see two red balloons and three blue balloons. How many balloons are there altogether?").

The maximum total raw score was 6. Cronbach's alpha of this subscale was .85. The score on arithmetic operations was defined as the total accuracy score (% correct items).

Domains of mathematics in elementary school.

Procedural calculation. The procedural calculation abilities of the children were tested using a subtest of the *Cognitive Developmental Skills in Arithmetics* (*Cognitieve Deelhandelingen van het Rekenen* [*CDR*]; Desoete & Roeyers, 2006). The *CDR* is a 90-item test that embraces different subskills, including procedural abilities (mathematical procedural problems, such as number splitting and addition/subtraction by regrouping, presented in a number problem format; e.g., "12 – 9 = __"; *P*). The *CDR* consists of three parallel test versions: grade 1-2, grade 3-4, and grade 5-6. In the current study, due to the age range of the children, the first version was used. Cronbach's alpha was .74 for this subtest. The score on procedural calculation was defined as the total accuracy expressed as a z-score using the mean and standard deviation of the normed sample of the test.

Number fact retrieval. The *Arithmetic Number Facts Test* (*Tempotest Rekenen* [*TTR*]; De Vos, 1992) is a numerical facility test assessing the memorization and automatization of arithmetic facts. In first grade, two arithmetic number fact problem subtests are administered: addition and subtraction. Participants were instructed to solve as many items as possible in two minutes; they could work one minute on every subtest. Cronbach's alpha for both subtests was .92. The score on number fact retrieval was defined as the total accuracy expressed as a z-score using the mean and standard deviation of the normed sample of the test.

Word/language problems. The word/language problem abilities were tested using three subtests of the *CDR* (Desoete & Roeyers, 2006): linguistic abilities (one-sentence mathematical problems in a word problem format; e.g., "1 more than 5 is__"; *L*); mental representation abilities (one-sentence mathematical problems that go beyond a superficial approach of keywords and that require a mental representation to prevent errors; e.g., "47 is 9 less than __"; *M*); and contextual abilities (more-than-one-sentence mathematical problems in a word problem format; e.g., "Wanda has 47 cards. Willy has 9 cards less than Wanda. How many cards does Willy have?"; *C*). As such, the word/language problems component was assessed by different subtests, incorporating aspects of simplicity (*L*) versus complexity (*C*) and items with (*M*) versus without (*L*) mental representation involved. Cronbach's alpha was .88 for all word/language problems. The score on word/language problems was defined as the total accuracy expressed as a z-score using the mean and standard deviation of the normed sample of the test.

Time-related competences. *The Time Competence Test* (*TCT*; *Test Tijdscompetentie*; Burny, 2012; Burny et al., 2012) is a test battery developed to assess the mastery of time-related competences in elementary school children. The test consists of four domains: clock reading, time intervals, time-related word problems, and calendar use. The *TCT* consists of four parallel tests that are associated with the ability levels in each grade (grade 1, grade 2, grade 3, and grade 4-6). The items are each time based on the Flemish elementary mathematics curriculum of the specific grade(s). The *TCT-1* includes 14 items. The *TCT* has already been used to assess the time-related competences of Flemish elementary school children (Burny, 2012). Cronbach's alpha was .74. The score on time-related competences was defined as the total accuracy expressed as a z-score using the mean and standard deviation of the normed sample of the test.

Analyses

In a first step, a multivariate analysis of variance was used to compare the two groups of children on early numerical competencies in preschool, and on the domains of mathematics in elementary school. Moreover, both groups were not only compared to each other, but also to the normed population of the standardized tests in elementary school, in order to compare them to a reference point. To this end, all scores on the domains of mathematics were expressed as z-scores using the mean and standard deviation of the normed sample of the test. In order to be able to use a composite score, a general math index was created, which was calculated as the average z-score of all four domains of mathematics. A series of Bonferroni-corrected (*p*-value divided by four) one sample t-tests was used to compare the z-scores of the four domains of mathematics against the normed samples reference point (i.e., a z-score of zero).

Second, a correlation analysis was conducted to assess the linear relationships between the various early numerical competencies and the domains of mathematics in both TD children and children with ASD. In order to enable comparison with previous research that uses one single composite score, the general math index was included.

Finally, a multivariate regression analysis was conducted with the four domains of mathematics as outcome variables and the early numerical competencies as predictors. Group was included as factor to compare the TD children with the children with ASD. Starting from a model in which all five predictors, as well as all two-way interactions between the five predictors and the factor group were included, a backward selection procedure was applied to reveal significant predictors. After describing this final model, FSIQ was added as a control variable in order to determine which effects remained significant after inclusion of this covariate. Other control variables were not included, because they did not show an overall significant correlation pattern with the outcome variables in both groups (p > .050). All analyses were performed in SPSS Version 21.0 (IBM Corp., 2012).

RESULTS

Comparison of children with and without autism spectrum disorder

A multivariate analysis of variance indicated no significant differences in early numerical competencies at preschool age between the two groups, $F(5, 81) = 1.17$, p = .330 (see Figure 1).

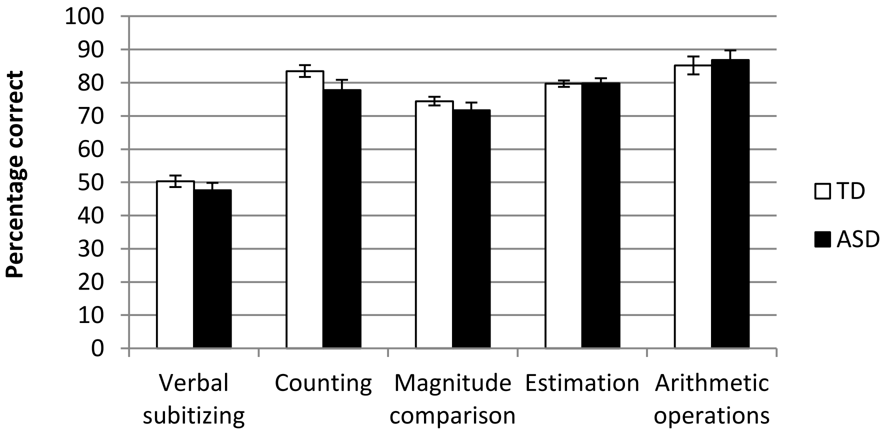

Figure 1. Early numerical competencies in typically developing children (TD) and children with autism spectrum disorder (ASD).

However, there was a significant difference between TD children and children with ASD for the domains of mathematics in first grade, $F(4, 82) = 4.45$, $p = .003$, with TD children scoring higher than the children with ASD. This difference remained significant even after controlling for FSIQ (this control variable was significantly related to the scores on the domains of mathematics), $F(4, 80) = 2.78$, $p = .032$. When looking at the univariate test results, there was only a significant difference for the domains of number fact retrieval and word/language problems, $F(1, 83) = 4.44$, $p = .038$ and $F(1, 83) = 8.18$, $p = .005$ respectively. Children with ASD obtained lower scores on these domains compared to the TD children (see Figure 2).

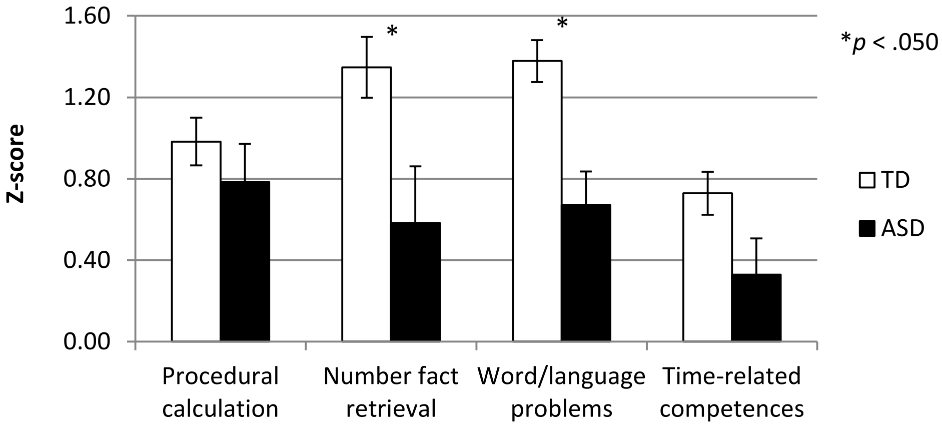

Figure 2. Domains of mathematics in typically developing children (TD) and children with autism spectrum disorder (ASD).

When comparing the children with ASD to the normed samples of the tests, the children with ASD turned out to score higher than the normed samples for the general math index, $t(32) = 3.54$, $p = .001$. The same pattern of results held for the domains of procedural calculation and word/language problems, $t(32) = 4.19$, $p < .001$, and $t(32) = 4.07$, $p < .001$ respectively (see Figure 3). After applying a Bonferroni correction, there was no significant difference between the ASD group and the normed samples for the domains of number fact retrieval and time-related competences, $t(32) = 2.09$, $p = .044$ and $t(32) = 1.83$, $p = .076$ respectively (see Figure 3).

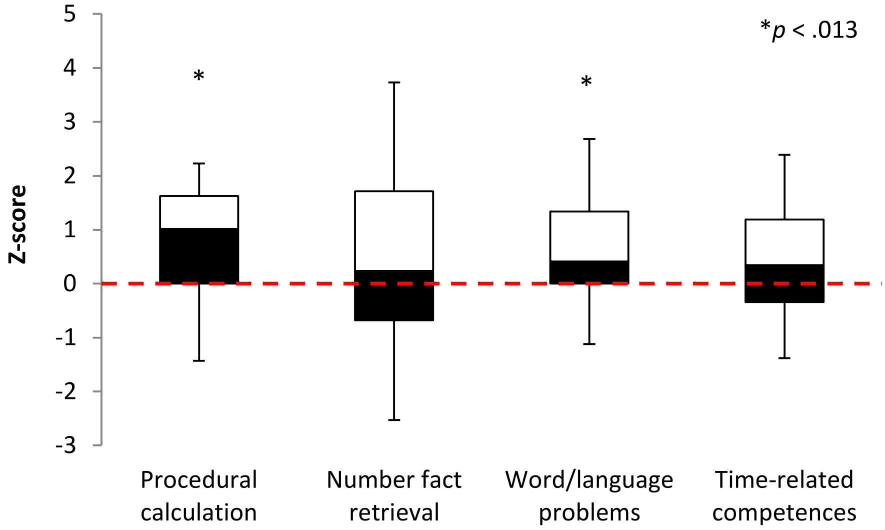

Figure 3. Domains of mathematics for children with autism spectrum disorder compared to the normed population.

Bivariate relations among the constructs

Table 2 provides the correlation matrix of the early numerical competencies in preschool, the general math index in elementary school, the four separate domains of mathematics, and FSIQ in both TD children and children with ASD.

Early numerical competencies were closely interrelated in both groups of children, mostly showing significant correlations. The domains of mathematics also intercorrelated significantly, with positive values for all. Significant correlations could be found between early numerical competencies and both the general math index, and the domains of mathematics separately. Overall, correlations for TD children and children with ASD showed a similar pattern, but in some instances the correlations in the ASD group were significantly stronger compared to TD children. This could be observed for some correlations between verbal subitizing or counting and later mathematics, as well as for some intercorrelations between the domains of mathematics (Fisher r-to-z transformations, $p < .050$; see Table 2).

Table 2. *Correlations between early numerical competencies, domains of mathematics, and full scale IQ*

		VS[a]	C[b]	MC[c]	E[d]	AO[e]	GMI[f]	PC[g]	NFR[h]	WLP[i]	TRC[j]
VS[a]	TD	-									
	ASD	-									
C[b]	TD	.39**	-								
	ASD	.59***	-								
MC[c]	TD	.38**	.18	-							
	ASD	.34^t	.34*	-							
E[d]	TD	-.44**	-.31*	-.28*	-						
	ASD	-.45*	-.34^t	-.41*	-						
AO[e]	TD	.28*	.47***	.18	-.28*	-					
	ASD	.50**	.53**	.14	-.24	-					
GMI[f]	TD	.29*	.44**	.31*	-.29*	.38**	-				
	ASD	$\underline{.68}$***	.58***	.35*	-.37*	.42**	-				
PC[g]	TD	.21	.39**	.08	-.30*	.15	.70***	-			
	ASD	$\underline{.60}$***	.46**	.15	-.43*	.35*	.82***	-			
NFR[h]	TD	.23	.39**	.32*	-.24^t	.28*	.73***	.36**	-		
	ASD	$\underline{.73}$***	.46**	.38*	-.43*	.35*	$\underline{.89}$***	$\underline{.70}$***	-		
WLP[i]	TD	.23	.30*	.18	-.12	.34*	.64***	.31*	.18	-	
	ASD	.54**	.50**	.35*	-.32^t	.40*	$\underline{.83}$***	.60***	$\underline{.61}$***	-	
TRC[j]	TD	.11	.09	.26^t	-.11	.29*	.66***	.26^t	.26^t	.40**	-
	ASD	.30^t	$\underline{.51}$**	.22	.03	.29^t	.73***	.41*	.47**	.63***	-
FSIQ[k]	TD	.13	.15	.32*	-.34*	.27*	.35**	.23^t	.15	.34*	.30*
	ASD	.35*	$\underline{.50}$**	.24	-.23	.36*	.51**	.42*	.43*	.59***	.28

Note. $^t p < .100$, $*p < .050$, $**p < .010$, ***Bonferroni-corrected ($p < .001$); underlined correlations indicate a significantly higher correlation than in the other group (Fisher r-to-z transformation, $p < .050$); TD = typically developing children, ASD = children with autism spectrum disorder; [a]Verbal subitizing, [b]Counting, [c]Magnitude comparison, [d]Estimation, [e]Arithmetic operations, [f]General math index, [g]Procedural calculation, [h]Number fact retrieval, [i]Word/language problems, [j]Time-related competences, [k]Full scale IQ.

Predictive value of early numerical competencies for later mathematics

A multivariate regression analysis was conducted with the four domains of mathematics as outcome variables. Starting from a model in which all five predictors as well as the two-way interactions between the five predictors and group were included, a backward selection procedure revealed the following significant predictors at multivariate level: verbal subitizing, $F(4, 79) = 5.23$, $p = .001$; counting, $F(4, 79) = 2.62$, $p = .041$; and verbal subitizing × group, $F(4, 79) = 3.14$, $p = .019$. The significant intercorrelations between predictors imposed no problem for multicollinearity, as all VIF values were close to 1 (Field, 2009).

At the univariate level, there was a significant effect of verbal subitizing on procedural calculation, number fact retrieval, and word/language problems, $F(1, 82) = 6.74$, $p = .011$, $F(1, 82) = 16.67$, $p < .001$, and $F(1, 82) = 5.62$, $p = .020$ respectively. This term resulted in on average higher scores in the outcome variables procedural calculation, number fact retrieval, and word/language problems, with increasing values for verbal subitizing. However, there was also a significant effect of the verbal subitizing × group interaction on number fact retrieval, $F(1, 82) = 11.32$, $p = .001$, resulting in a differential effect of verbal subitizing on number fact retrieval for both groups: Whereas verbal subitizing was a significant predictor for number fact retrieval in the ASD group, $t(83) = 4.58$, $p < .001$, it was not for the TD children, $t(83) = 1.02$, $p = .311$. For counting, there was a significant positive effect on procedural calculation, $F(1, 82) = 6.31$, $p = .014$, word/language problems, $F(1, 82) = 5.34$, $p = .023$, time-related competences, $F(1, 82) = 4.59$, $p = .035$, and a trend for number fact retrieval, $F(1, 82) = 3.88$, $p = .052$. Higher values for counting were associated with on average higher values for the outcome variables. Table 3 provides an overview of the estimated regression coefficients and the standard errors of the model.

Table 3. *Estimated standardized regression coefficients and standard errors for the multivariate regression model without full scale IQ*

		TD (*n* = 54)		ASD (*n* = 33)	
		β	*± SE*	*β*	*± SE*
Procedural calculation	Verbal subitizing	.09	±.12	.47	±.17
	Counting	.27	±.11	.27	±.11
Number fact retrieval	Verbal subitizing	.16	±.15	.99	±.22
	Counting	.27	±.14	.27	±.14
Word/language problems	Verbal subitizing	.10	±.11	.37	±.15
	Counting	.22	±.10	.22	±.10
Time-related competences	Verbal subitizing	.00	±.12	.15	±.17
	Counting	.23	±.11	.23	±.11

Note. TD = typically developing children, ASD = children with autism spectrum disorder.

In a next step, FSIQ was added as a control variable to the model, because it correlated significantly with the outcome variables (see Table 2). After controlling for FSIQ, the effects of verbal subitizing on the different domains of mathematics remained unchanged. There still was a significant positive effect of verbal subitizing on procedural calculation and word/language problems, with $F(1, 80) = 5.43$, $p = .022$ and $F(1, 80) = 5.20$, $p = .025$ respectively. There also remained an effect of verbal subitizing on number fact retrieval for the ASD group, $t(82) = 4.33$, $p < .001$. For counting, the positive effects on procedural calculation and number fact retrieval remained unchanged, with $F(1, 80) = 5.09$, $p = .027$ and $F(1, 80) = 3.00$, $p = .087$ respectively. However, the effect of counting on word/language problems and time-related competences disappeared when taking into account FSIQ, $F(1, 80) = 2.14$, $p = .147$ and $F(1, 80) = 2.45$, $p = .122$ respectively. An overview of the estimated regression coefficients and the standard errors of the model with FSIQ included can be found in Table 4.

Table 4. *Estimated standardized regression coefficients and standard errors for the multivariate regression model with full scale IQ as control variable*

		TD (*n* = 54)		ASD (*n* = 33)	
		β	*± SE*	*β*	*± SE*
Procedural calculation	Verbal subitizing	.08	±.12	.42	±.17
	Counting	.24	±.11	.24	±.11
Number fact retrieval	Verbal subitizing	.15	±.15	.95	±.22
	Counting	.24	±.14	.24	±.14
Word/language problems	Verbal subitizing	.09	±.10	.33	±.14
	Counting	.13	±.09	.13	±.09
Time-related competences	Verbal subitizing	.17	±.11	.13	±.17
	Counting	.17	±.11	.17	±.11

Note. TD = typically developing children, ASD = children with autism spectrum disorder.

DISCUSSION

The current study aimed at investigating the predictive value of five early numerical competencies at preschool age for four domains of mathematics in first grade. Because previous research comparing the mathematical abilities of children with ASD and TD children is scarce (and even unexplored at preschool age), the current study compared the performance of the two groups of children both at preschool age and in first grade in a first step. Next, it was investigated which of the early numerical competencies were most predictive for first grade mathematics performance, differentiated into four domains of mathematics, in TD children and children with ASD.

General findings

The current study compared the five early numerical competencies as outlined in the review of N. C. Jordan and Levine (2009) in TD children and children with ASD at preschool age (5-6 years). Results revealed no significant differences between the two groups of high-functioning preschoolers, suggesting a similar early number processing in children with and without ASD at this young age. This finding is in line with some previous studies that investigated mathematical abilities in children with ASD from a between-group perspective, but at a later age (Chiang & Lin, 2007; Gagnon et al., 2004; Iuculano et al., 2014; Jarrold & Russell, 1997).

In contrast, when comparing both groups of children in first grade, children with ASD obtained significantly lower scores than TD peers on the domains number fact retrieval and word/language problems, even after controlling for FSIQ. This finding seems to undo the aforementioned similarity with previous research on this topic. However, when comparing the ASD group to the normed samples of the test, the children with ASD appeared to score average on the domains of number fact retrieval and time-related competences, and significantly higher on the domains of procedural calculation and word/language problems. In this way, the current results are consistent with previously reported average to good mathematical abilities of children with ASD compared to the normed population (Chiang & Lin, 2007; Church, Alisanski, & Amanullah, 2000). A likely explanation for the mathematical proficiency of both the TD children and the children with ASD is the selective sample of the current study, as indicated by the values of FSIQ and socioeconomic status (SES) that are significantly higher than in the general population. The descriptive characteristics of the sample suggest the inclusion of high-functioning children with a high socioeconomic background, probably resulting in more learning opportunities and numerical stimulation (N. C. Jordan, Kaplan, Olah, & Locuniak, 2006; Melhuish et al., 2008). Indeed, parental social class and educational level have proven to be predictive for mathematics achievement (N. C. Jordan & Levine, 2009). The fact that no significant correlations were found between SES and early numerical competencies or domains of mathematics in our sample, could be due the inclusion of this upper bound SES group, leading to a lack of variation in scores.

Results of the correlation matrix showed that the five early numerical competencies were frequently significantly intercorrelated in the expected direction (positive when both competencies are positively operationalized and negative with estimation, which is operationalized as a percentage of error). The domains of mathematics also showed significant positive interrelations. Moreover, all five early numerical competencies illustrated an expected pattern of correlations with the domains of mathematics. The highest correlations could be observed for counting and arithmetic operations in both groups and for verbal subitizing in the ASD group.

This pattern of results was somehow reflected in the multivariate regression analysis, presenting both counting and verbal subitizing as important predictors for mathematics performance in first grade in both groups of children. Whereas verbal subitizing was the strongest predictor for mathematics in the ASD group, counting was the strongest predictor in TD children. Arithmetic operations tested in preschool did not have a significant unique contribution to later mathematics when added simultaneously with verbal subitizing and counting into the same model, perhaps because at this young age, almost all children use counting strategies to solve this simple addition and subtraction exercises (Baroody, 1987; Butterworth, 2005): Before children learn number facts that can be retrieved from long-term memory, they rely on counting procedures to solve these problems (Fuchs et al., 2009).

The univariate tests of the regression analysis allowed us to interpret the results of our multicomponential approach. In children with ASD, verbal subitizing was the strongest predictor for all domains of mathematics, except for time-related competences. In TD children, verbal subitizing was only predictive for procedural calculation and word/language problems, and had moreover a smaller predictive value than counting. The stronger predictive value of verbal subitizing in children with ASD could perhaps be due to the importance of perceptual characteristics in this task, because children with ASD are known to show an enhanced perceptual functioning (Mottron, Dawson, Soulieres, Hubert, & Burack, 2006). Although not causing a superior performance on verbal subitizing, the task could be more appealing to children with ASD. It is likely that children with ASD use different strategies or cues when solving tasks, which may be, in turn, more related to their strategy use in later mathematics (Gagnon et al., 2004; Iuculano et al., 2014; Jarrold & Russell, 1997). Future research should however illuminate if this assumption holds and why only some domains of mathematics seem to be influenced.

Although counting was a significant predictor of later mathematics performance in both groups of children, the predictive value of counting was stronger in TD children. This confirms the well-established role of counting as a key precursor for later mathematics performance as presented in previous research (Aunola et al., 2004; Desoete et al., 2009; Stock, Desoete, & Roeyers, 2009; Stock et al., 2010). At first, counting seemed to be a good predictor for all domains of mathematics when investigated in first grade. However, when controlling for FSIQ, counting was most predictive for procedural calculation and to a lesser extent (showing only a marginally significant result) for number fact retrieval. Both domains of mathematics are operationalized in a similar way, providing addition and subtraction exercises in a number problem format. As such, it seems logical to observe parallels between these exercises because they are closely linked. However, whereas number fact retrieval consists of timed basic arithmetic facts easily retrieved from long-term memory, procedural calculation requires the use of procedures and computational strategies such as number splitting and addition/subtraction by regrouping to solve the task at hand and exercises are untimed (Domahs & Delazer, 2005). As such, children may be in need of counting procedures when acquiring the skills to solve procedural tasks and only favor memory-based retrieval of answers after increasingly efficient counting and decomposition strategies help them to establish associations in long-term memory (Fuchs et al., 2009; Koponen, Aunola, Ahonen, & Nurmi, 2007). Due to their untimed character, the exercises may evoke more counting strategies then when children solve exercises under time restraints. Most previous research investigating the predictive value of counting uses one composite math score, not allowing us to differentiate between different domains of mathematics (e.g., Aunio & Niemivirta, 2010; Aunola et al., 2004; Stock et al., 2010). However, a relationship between counting and calculation performance has already been demonstrated (e.g., Geary, Bowthomas, & Yao, 1992; Johansson, 2005; Koponen et al., 2007).

Strengths and limitations

This study adds to the scarce literature on mathematical abilities in children with ASD, not only by comparing the mathematical abilities at elementary school age, but also by taking into account the early numerical competencies at preschool level. Moreover, this study is the first to investigate the predictive value of early numerical competencies measured at preschool age for mathematics performance in first grade in a group of children with ASD, allowing us to gain insight into this important transition period before children enter elementary school. Previous research has reached consensus that children's school transition from preschool to first grade entails a particularly vital period, because children's competences transit from primary qualitative abilities to more complex and culturally bound secondary mathematical abilities, forming a basis that affects subsequent achievement trajectories (Aunio & Niemivierta, 2010; Geary, 2000; Normandeau & Guay, 1998). In this way, the current study goes beyond comparing the abilities of two groups of children, but points toward possible differences in predictive processes or cues used to perform mathematical tasks in elementary school.

The current study used a multicomponential approach on the predictors as well as on the outcome variables, whereas previous research focused on one single aspect of mathematics or applied one composite math score. Recent research emphasized the importance of incorporating such a multicomponential approach and strongly advocates this in future research (J. A. Jordan et al., 2009; Mazzocco, 2009; Simms, Cragg, Gilmore, Marlow, & Johnson, 2013).

However, some limitations should be borne in mind when interpreting the results of the current study. First, the current study included a substantially smaller sample size compared to previous studies investigating the predictive value of multiple early numerical competencies (e.g., N. C. Jordan et al., 2007; N. C. Jordan et al., 2009; Stock et al., 2009, 2010). Although these studies indeed incorporate a much larger sample, we should be aware of the fact that only TD children are included. The sample size of the current study is however comparable with other studies on mathematics including the clinical group condition of ASD (e.g., Gagnon et al., 2004; Iuculano et al., 2014; Jarrold & Russell, 1997). Nevertheless, the smaller sample size could result in a decreased probability to detect possible predictors or interactions between the predictors and group condition. This probability was also diminished by the multicomponential approach for both predictors and outcomes, leading to a model in which many variables were included. Second, the current study contained a highly selective sample, with only high-functioning children with ASD. Moreover, both groups proved to show high scores on FSIQ and SES, suggesting that perhaps mostly well-educated and highly motivated parents decided to participate in the study. This sample selection bias puts limits to the generalizability of the findings to lower functioning children with a lower socioeconomic background. Finally, it is important to note that most of the instruments have never been used in an ASD group before. However, standardized measures already validated in TD children were used whenever possible. The experimental tasks were operationalized similar to previous research on this topic, resulting in similar effects (*elbow effect* for the subitizing task, *ratio dependency* for the magnitude comparison task, similar PAE scores for the number line estimation task). All experimental measures were used in TD populations or children with MLD in previous research (e.g., Berteletti, Lucangeli, Piazza, Dehaene, & Zorzi, 2010; Ceulemans et al., 2014; Praet et al., 2013; Stock et al., 2007). Nevertheless, we should be aware that the specific operationalization of concepts might have its influence on the results.

Implications and conclusion

Based on the results of the current study, mathematics should not be a concern in children with ASD, at least when they have higher than average FSIQ and SES scores. At preschool age, the children with ASD scored similar on early numerical competencies to the TD children included in the study. In first grade, our ASD group scored significantly lower on the four domains of mathematics than the TD group, but average to high compared to the normed samples of the tests. Therefore, it can be concluded that the foundation of mathematical development in high-functioning children with ASD stemming from a high socioeconomic background might be similar to that of TD peers in general.

When trying to predict the mathematical abilities of children with ASD from preschool age, while bearing in mind our specific high-functioning group with well-educated and well-employed parents, our results suggest that a test battery should at least include a verbal subitizing task and a counting task. Indeed, these variables are most predictive for mathematics in first grade for this group of children. Future research should investigate whether these predictions hold at later age as well, or whether these precursors are only predictive for initial mathematics achievement in first grade. This is especially the case for counting, which is an important antecedent in the development of calculation strategies (Johansson, 2005), but only as an early solution procedure that facilitates the formation of associations in long-term memory between the problem presented and the answer. Over time, new and more accurate fact retrieval strategies are used for solving arithmetic problems (Johansson, 2005), which could perhaps alter the predictive values. Regarding verbal subitizing, future research should investigate more in detail why this ability is particularly predictive for first grade mathematics in children with ASD and why it affects only some domains of mathematics.

To conclude, no concerns should be raised over the mathematical abilities of high-functioning children with ASD with a high socioeconomic background in general, because these children score on group level comparable or even higher than the general first-grade population. This finding does, however, not detract from the importance of individual assessment and evaluation in the classroom. When trying to predict later mathematical performance in first grade, both counting and verbal subitizing seem to be important predictors to evaluate and to incorporate in an assessment battery at preschool age. However, whereas counting is most informative in TD children, verbal subitizing is most predictive in children with ASD.

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CHAPTER 6

GENERAL DISCUSSION

The main goal of this dissertation was to get more insight into the early numerical competencies and mathematical abilities of children with autism spectrum disorder (ASD). To this end, four empirical studies were conducted in which children with ASD were compared with a control group of typically developing children or with the normed population. This final chapter encloses a summary and discussion of the main findings. Additionally, limitations of the present studies and suggestions for future research are outlined. In conclusion, practical implications and recommendations are described.

RECAPITULATION OF RESEARCH GOALS AND MAIN FINDINGS

In the last decades, the field of *autism spectrum disorders* (*ASDs*) has been characterized by important breakthroughs, insights, and developments on several domains (G. Jones, 2006). One fiercely controversial topic has been the educational inclusion, as opposed to a self-contained setting, of children with ASD (Harrower, 1999; Harrower & Dunlap, 2001; Kauffman & Hallahan, 1995; Smith, 2012). Although few studies have actually investigated which setting is recommended for students with ASD (Harrower & Dunlap, 2001; Smith, 2012), there is yet a change noticeable in the educational field. Whereas historically, students with disorders have been segregated from their peers (Karagiannis, Stainback, & Stainback, 1996), there is now an increasing trend to include students with ASD and other disorders in general education classrooms, along with their typically developing peers (Fleury et al., 2014; McDonnell, 1998; Smith, 2012). This relatively rapid growth of the number of children with ASD in mainstream settings has led to a sense of urgency among practitioners and parents to insure they have knowledge of, and access to, the best educational provision for these children (G. Jones, 2006). Although students with ASD who score in the average range on standardized tests of cognitive functioning seem to be candidates for successful inclusion, they nevertheless put a challenge to teaching staff and therapists in terms of knowing how to accomplish certain academic goals and to reach the full potential of the children (Balfe, 2001).

Within this scope, there is a growing demand from teachers and practitioners for adapted educational techniques specifically on mathematics, as this seems to be a stumbling block for quite a large group of children with ASD (Department for Education and Skills, 2001; van Luit, Caspers, & Karelse, 2006). Despite this concern on the mathematical development of children with ASD, the amount of scientific research on this topic is scarce. This doctoral project aimed to fill this gap in existing research. We intentionally chose to investigate this topic on a behavioral level, in order to provide a first exploratory analysis of early numerical competencies and mathematical abilities in children with ASD. We considered this as an important first step that could guide further research on an explanatory level if needed. This doctoral dissertation was guided by three main research goals. The first goal was to explore the performance profile of children with ASD on five early numerical competencies compared to that of typically developing children at two time slots in preschool: the second and the third year of preschool. The second goal enclosed the comparison of the performance of children with ASD and typically developing children on four important domains of mathematics in elementary school. Finally, our third research goal was to investigate the predictive value of early numerical competencies at preschool age for the domains of mathematics in elementary school and to compare the pattern of results between children with and without ASD. These three research goals were addressed in four chapters.

In *Chapter 2*, five *early numerical competencies* (*verbal subitizing*, *counting*, *magnitude comparison*, *estimation*, and *arithmetic operations*) were investigated in 20 high-functioning children with ASD and 20 typically developing children. These early numerical competencies were tested in the second year of preschool (4 to 5 years of age), during which little attention and very few instruction is paid to numbers within the Flemish curriculum. Overall, no significant differences could be found between the two groups of children, indicating similar early number processing in children with and without ASD aged 4 to 5 years.

In *Chapter 3*, the same five early numerical competencies were investigated, but in the third year of preschool (5 to 6 years of age), a period that can be considered as a transition moment at which numbers become increasingly integrated within the educational curriculum in order to prepare children to start the first grade of elementary school. The five early numerical competencies were investigated in 30 high-functioning children with ASD and 30 typically developing children. Again, no significant differences could be found between the two groups of preschoolers on the assumed foundations of mathematics. Despite the overall similarities between the children with and without ASD, some marginally significant results emerged. Children with ASD showed a trend toward a lower score on verbal subitizing accuracy and conceptual counting knowledge compared to typically developing children. Moreover, a descriptive difference between the two groups could be found for the performance on the dot pattern format of the estimation task. More specifically, children with ASD showed poor linear and logarithmic fits for the estimation of dot patterns on a number line, whereas typically developing peers endorsed good fits in both cases. This finding suggests a less developed nonsymbolic representation of number in children with ASD.

Chapter 4 complemented the chronological sequence of the previous studies, as it studied the performance of children with ASD on four domains of mathematics in elementary school (i.e., *secondary mathematical abilities*): *procedural calculation*, *number fact retrieval*, *word/language problems*, and *time-related competences*. The results of 121 elementary school children with ASD attending first to fourth grade of mainstream educational settings were compared to the scores of the normed samples of the standardized tests that were administered. The findings showed a profile of strengths, average abilities, and weaknesses in mathematics. More specifically, children with ASD showed a strength on word/language problems in grade 2 and 4 and a weakness on procedural calculation in grade 1 and time-related competences in grade 1 and 3.

Finally, in *Chapter 5,* we presented a longitudinal study focusing on the transition period from preschool to first grade. This study aimed at investigating the predictive value of the five early numerical competencies in the third year of preschool for the four domains of mathematics in first grade in 33 children with ASD and 54 typically developing peers. The pattern of results in both children with ASD and typically developing children was indicative for two important predictors at preschool level: verbal subitizing and counting. However, whereas verbal subitizing had the highest predictive value in the ASD group, counting was the strongest predictor in the typically developing group. In addition to these longitudinal patterns, the performance of the two groups was compared to each other at both time points (i.e., the third year of preschool and first grade). Furthermore, the results of the first graders on the four domains of mathematics were also compared to the normed samples of the standardized tests. Confirming the results of *Chapter 2* and *Chapter 3*, children with ASD showed similar early numerical competencies as typically developing preschoolers. In first grade, the children with ASD scored generally lower on mathematics than the typically developing control group, but similar to (for number fact retrieval and time-related competences) or higher than (for procedural calculation and word/language problems) the normed samples.

COVERING CONCLUSIONS AND DISCUSSION

Early numerical competencies in preschoolers with autism spectrum disorder

Several studies have lent support for the predictive value of verbal subitizing (e.g., Reigosa-Crespo et al., 2012; Schleifer & Landerl, 2011), counting (e.g., Aunola, Leskinen, Lerkkanen, & Nurmi, 2004; LeFevre et al., 2006), magnitude comparison (e.g., De Smedt, Verschaffel, & Ghesquiere, 2009; Landerl, Bevan, & Butterworth, 2004), estimation (e.g., Geary, Hoard, Nugent, & Byrd-Craven, 2008; Siegler & Booth, 2004), and arithmetic operations (e.g., Hanich, Jordan, Kaplan, & Dick, 2001; N. C. Jordan, Glutting, & Ramineni, 2010) for typical as well as atypical mathematical performance at later age. Taking this evidence into account, we thought it would be worthwhile to extend this knowledge by applying it to another condition, namely ASD, because practitioners often report mathematical difficulties in children with ASD at elementary school age (Department for Education and Skills, 2001). As such, expanding the aforementioned findings that are already well-established in typically developing children and children with a *mathematical learning disorder* (*MLD*) allowed us to investigate the early mathematics foundation in children with ASD even before elementary school. Considering the practitioners' concerns, studying early predictors can be of crucial importance in light of intervention, knowing that early success may set a positive life-course trajectory (Kern & Friedman, 2008). Intervention programs have the potential to reduce disparities in mathematics achievement (N. C. Jordan, Glutting, Dyson, Hassinger-Das, & Irwin, 2012; Tzuriel, Kaniel, Kanner, & Haywood, 1999; Weiland & Yoshikawa, 2013). Beginning intervention as early as possible is likely to be beneficial: Prevention (if possible) is preferable to remediation because of the difficulty of remediating math failure later (e.g., Slavin, Karweit, & Wasik, 1993; Young-Loveridge, 2004).

The results of this dissertation suggest that both in the second (*Chapter 2*) as well as in the third year of preschool (*Chapter 3*), children with ASD show similar early number processing as typically developing children. On group level, no significant differences were found between the two groups of preschoolers for all early numerical competencies that were investigated. This suggests that children with ASD can start elementary school with an adequate mathematical basis that equals the basis of peers without ASD. However, some slight differences could be observed between the two studies described in *Chapter 2* and *Chapter 3*: In the second year of preschool absolutely no differences could be found between children with and without ASD (*Chapter 2*), but in the third year of preschool there were some marginally significant differences between the two groups (*Chapter 3*). First, several explanations may be provided for these subtle differences between the second and the third year of preschool. Next, we focus on why these small differences may have occurred for some early numerical competencies in particular, by looking at the possible influence of cognitive characteristics on early numerical development.

Explaining the subtle differences between the second and third year of preschool. First of all, we acknowledge the possible impact of early schooling when considering the differences between the results of *Chapter 2* and *Chapter 3*. Although there exists already large variation in early numerical skills before entering preschool (N. C. Jordan & Levine, 2009; Powell & Fuchs, 2012), early schooling may impact upon this initial level of functioning, hereby enlarging individual differences between children (Morgan, Farkas, & Wu, 2009). One theoretical account in this respect is the *cumulative growth model* (Aunola et al., 2004; Morgan et al., 2009), which assumes that children with more mathematical knowledge before entering preschool keep adding to this knowledge and become increasingly skilled over time, whereas children with less knowledge learn at a relatively slower rate (Morgan et al., 2009). In educational research, this phenomenon has also been referred to as the *Matthew effect* (Scarborough & Parker, 2003; Stanovich, 1986). Extending this train of thought, it is possible that for some early numerical competencies typically developing children benefit more from the increased focus on numbers in the educational curriculum of the third year of preschool than children with ASD.

A second possible explanation for the differences between the second and the third year of preschool, which also fits within the cumulative growth account, is the impact of early home experiences. With the increased focus on numbers in the third and last year of a preschool setting, parents may realize the importance of early numerical skills and stimulate their children to a greater extent in the third year of preschool than during previous years. Several studies have demonstrated that such early numerical home experiences may, in turn, lead to better numerical skills (e.g., Kleemans, Peeters, Segers, & Verhoeven, 2012; LeFevre et al., 2009; Melhuish et al., 2008; Pan, Gauvain, Liu, &

Cheng, 2006). Whereas this elevated emphasis on numerical interactions in the third year of preschool may be the case in typically developing children, it is not inconceivable that parents of children with ASD pay more attention to other, more relevant or salient, factors for their children with ASD at that age. A diagnosis of ASD, for example, can have a great impact on the family, with burden and family stress peaking at the time of the initial diagnosis (e.g., Howlin & Asgharian, 1999; Stuart & McGrew, 2009). Keeping in mind the fact that an official diagnosis of ASD is often not made until the child is 4 or 5 years old (Chakrabarti & Fombonne, 2005; Wiggins, Baio, & Rice, 2006), the preschool years might be considered as a period during which parents of children with ASD mainly learn how to cope with this new reality and seek appropriate support from social services. In this respect, it might be that – for parents of children with ASD – numerical stimulation or focusing on mathematical development may only become of interest during elementary school. For parents of typically developing children, this focus may burgeon earlier on. Research showed indeed that parents of children with ASD do worry about learning difficulties, but this was only demonstrated in elementary school children or adolescents (Lee, Harrington, Louie, & Newschaffer, 2008). As such, this difference in focus could give rise to the emergent differences in early numerical competencies between the two groups in the third year of preschool.

Finally, we should also take into account that the sample sizes of the two studies were not equal. Maybe, because of the smaller sample size in *Chapter 2*, no significant differences could be detected (Field, 2009). Likewise, it is possible that with a larger sample size in *Chapter 3*, the observed trends would turn significant (Field, 2009). However, future research with larger samples is needed to clarify whether the observed trends of *Chapter 3* were coincidental in nature or whether the early numerical competencies of children with ASD and typically developing children truly differ at both moments in preschool.

Do cognitive characteristics of autism spectrum disorders influence early numerical competencies? Although longitudinal research with a large sample of children should be conducted first to confirm or refute differences between children with and without ASD in the second and the third year of preschool, we may wonder why differences were only evident in some of the early numerical competencies in this doctoral research. In our opinion, differences may have especially occurred in those competencies on which autism-specific information processing characteristics have their largest influence. Our findings in *Chapter 3* indicated a trend toward lower scores on conceptual counting knowledge and verbal subitizing, and a difficulty in estimating the value of dot patterns in children with ASD in the third year of preschool. The possible impact of autism-specific information processing characteristics upon each of these findings will be elaborated upon below.

First, conceptual (counting) knowledge involves interconnected and meaningful knowledge (Baroody, 2003; Hiebert & Lefevre, 1986). From a historical perspective, conceptual mathematical knowledge has been linked to the *incidental learning theory* and the *meaning theory* (Baroody, 2003). According to the incidental learning theory, children should explore the world and actively construct their own understanding (Baroody, 2003). Similarly, the meaning theory advocates the meaningful comprehension of mathematical relations, in association with the understanding of its mathematical and practical significance (Baroody, 2003; Brownell, 1935). Both theories can be connected to the line of research indicating that individuals with ASD show a distinction between mechanical or procedural skills and conceptual skills, with the latter requiring more complex information processing, reasoning, and logical analysis (Goldstein, Minshew, & Siegel, 1994; Minshew, Goldstein, & Siegel, 1995; Minshew, Goldstein, Taylor, & Siegel, 1994). This differentiation between procedural and conceptual skills in children with ASD can be explained by the *weak central coherence* (*WCC*) *account* (Frith & Happé, 1994; Noens & van Berckelaer-Onnes, 2005). The drive for central coherence seen in typically developing individuals helps them to make sense of something and to extract meaning, whereas the preferred focus on details in children with ASD might jeopardize such adequate sense-making (Noens & van Berckelaer-Onnes, 2005). Although these findings of impaired conceptual skills in the presence of intact procedural skills were only demonstrated for the field of literacy and not for mathematics (Goldstein et al., 1994; Minshew et al., 1994), this doctoral dissertation suggests that this line of reasoning might perhaps be extrapolated to the field of mathematics.

Second, we found a trend for lower scores on verbal subitizing accuracy (i.e., more errors in the enumeration of small numerosities of up to three or four items) in children with ASD (*Chapter 3*). This is in contrast with previous studies demonstrating no between-group differences between typically developing children and children with ASD in accuracy rates on verbal subitizing tasks (Gagnon, Mottron, Bherer, & Joanette, 2004; Jarrold & Russell, 1997). However, the children in our sample (5-6 years) were younger (*Chapter 3*) than the individuals in the studies of Gagnon et al. (2004) and Jarrold and Russell (1997), who investigated participants aged 10-21 years and 6-18 years respectively. This could imply that the subitizing skills in our younger age group are still developing (Chi & Klahr, 1975), which may have resulted in different findings compared to these previous studies. Nevertheless, the current results might show some common grounds with previous findings when considering an explanation for the observed trend. In this regard, the WCC account may again step into the limelight. Due to their detail-focused information processing, children with ASD might have tried to use a serial counting strategy instead of a global subitizing process, which accords with the suggestions of Gagnon et al. (2004) and Jarrold and Russell (1997). However, due to the restricted presentation time of the stimuli (i.e., 123 ms) in the current study (*Chapter 3*), such a serial counting strategy may have been less successful and thus may have resulted in lower accuracy scores on the enumeration task. Regarding reaction times, no significant differences with typically developing children were observed, perhaps because none of the children could benefit from taking more time once the stimuli disappeared.

Finally, the descriptive differences between children with ASD and typically developing children observed for the estimation of dot patterns (*Chapter 3*) might be interpreted in quite a similar way as the previously described trends. Our findings indicated that, whereas typically developing children start to acquire the abilities to use a linear strategy for representing dot patterns on a number line, children with ASD show the most problems with this presentation format. This conclusion was deduced from their linear and logarithmic fits for this presentation format (see Figure 1). Indeed, linear and logarithmic R^2 values for children with ASD were (marginally) significantly lower compared to those of typically developing peers.

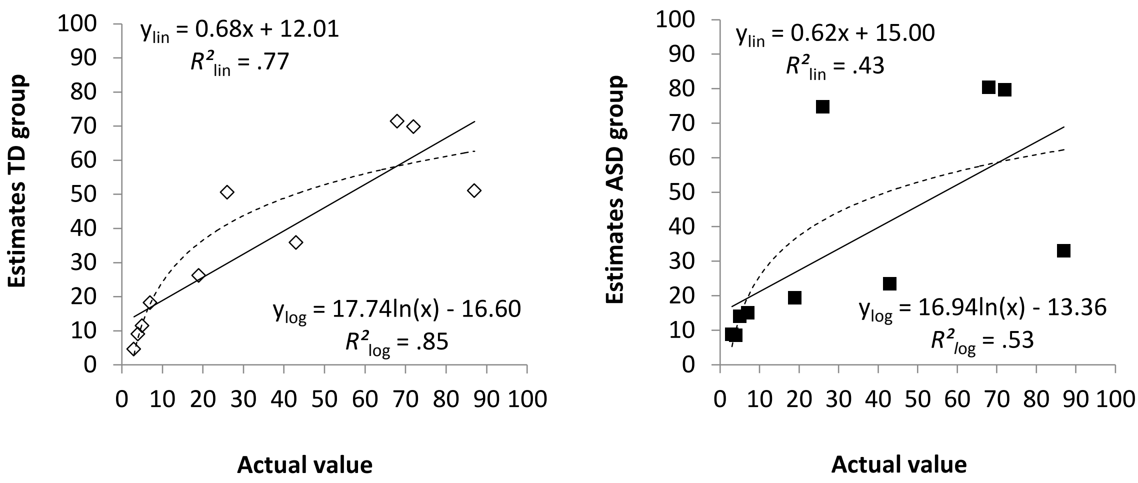

Figure 1. Linear and logarithmic fit for estimation of dot patterns in typically developing (TD) children and children with autism spectrum disorder (ASD).

These difficulties of children with ASD could be due to problems with estimating nonsymbolic stimuli on the number line, which was supported by the qualitative observation that children with ASD felt unsure when they needed to give an approximate answer, without the possibility to exactly determine the amount of dots by counting them. A focus on the separate dots may have prevented the children from making sense of the pattern as a whole, again reflecting the possible influence of a weaker central coherence in children with ASD (Frith, 1989). Additional research is however needed to investigate this assumption.

When expanding the line of thought on verbal subitizing and dot pattern estimation, a final remark on the observed trends with nonsymbolic stimuli should be made. In fact, one would also expect to find differences in the magnitude comparison task that is also using nonsymbolic stimuli, again, due to difficulties with the abstraction of meaning of "the bigger picture" (Happé, 1999). This could however not be confirmed in our studies (*Chapter 2* or *Chapter 3*). As such, further research is needed to clarify whether the observed trends can be replicated in a larger sample of children and if so, what the underlying causes might be.

Mathematical abilities in elementary school children with autism spectrum disorder

Chapter 4 and *Chapter 5* of this dissertation dealt with the mathematical abilities of children with ASD during the first four grades and grade 1 of elementary school respectively. Again, our main conclusion was that the mathematical abilities of children with ASD and typically developing children are by far more similar than different. This finding is consistent with previous between-group studies reporting average mathematical abilities in children with ASD compared to typically developing individuals (Chiang & Lin, 2007; Gagnon et al., 2004; Iuculano et al., 2014; Whitby & Mancil, 2009). When further discussing the results of *Chapter 4* and *Chapter 5*, three important reflections should be highlighted.

A developmental perspective on mathematics. In *Chapter 4*, we concluded that a profile of strengths, average abilities, and weaknesses emerged when investigating four domains of mathematics in elementary school children with ASD. When examining these data more closely, it is notable that only average to high mathematical abilities were found in fourth grade, whereas weaknesses only occurred in lower grades. This finding is suggestive of a developmental pathway in which high-functioning children with ASD eventually do not show any mathematical difficulties anymore in fourth grade. Previous studies often examined a larger age range, with an average age mostly equal to or higher than 9 years, which may explain why most studies using a between-group perspective reported average to good mathematical abilities in children with ASD (e.g., Chiang & Lin, 2007; Iuculano et al., 2014).

This developmental perspective of weaknesses in lower grades and average to high abilities in the highest investigated grade (i.e., grade 4) shows some resemblance with the theoretical *lag model* on mathematical development. The lag model (Aunola et al., 2004; Morgan et al., 2009) suggests that children with less mathematical knowledge can catch up with their higher skilled peers due to the provision of systematic instruction in school. This theoretical account seems to be in sharp contrast with the previously mentioned cumulative growth model (Aunola et al., 2004; Morgan et al., 2009) that could serve as an explanation for the differences in findings regarding the early numerical competencies between the second and the third year of preschool. A possible reason why these two accounts can coexist, is provided in the next paragraph.

Meanwhile, we should keep in mind that *Chapters 2, 3,* and *4* were cross-sectional in nature. No clear conclusions can be drawn without longitudinal research specifically focusing on the developmental trajectory of these mathematical abilities.

Are cognitive characteristics of autism spectrum disorders accountable for a combined cumulative growth – lag model? When taking together the previously mentioned accounts of the lag model and the cumulative growth model (Aunola et al., 2004; Morgan et al., 2009), it is possible to visualize or summarize them as in Figure 2. More specifically, our results could suggest that differences between children with ASD and typically developing children may funnel out to reach a maximum from the second year of preschool until first grade (cumulative growth model; see *Chapters 2, 3,* and *4*), followed by a decrease in differences, ending in similar mathematical abilities in fourth grade (lag model; see *Chapter 4*).

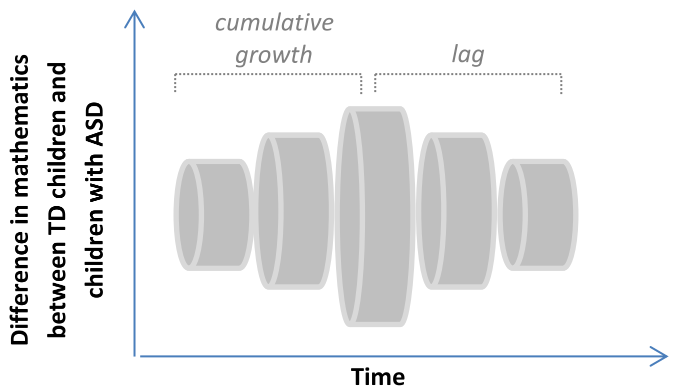

Figure 2. Schematic view of the combination of the cumulative growth model and lag model.

Note. TD = typically developing children;

ASD = children with autism spectrum disorder.

As already mentioned in the discussion on the early numerical competencies of children with ASD, it is possible that a weaker performance is only evident for mathematical abilities on which autism-specific characteristics have their largest influence. In this regard, it makes sense that a weakness in procedural calculation – and not number fact retrieval – was found (*Chapter 4*). Number fact retrieval appeals to rote memory and is taught systematically and straightforward. In contrast, procedural calculation requires computational strategies and related mathematical knowledge, for example, knowing that splitting numbers is necessary to solve an addition by regrouping task successfully. As such, they put a greater demand on executive functions and – despite the term "procedural" – require logical analysis, two factors that have proven to be impaired in children with ASD (Ozonoff, Pennington, & Rogers, 1991; Minshew et al., 1994). Similarly, time-related competences are abstract and implicit in nature.

However, autism-specific information processing characteristics might not only be reflected in the weaker performance on some of the mathematical domains, but they can also be involved in the determination of the specific "turning point" within the evolution of the combined cumulative growth – lag model. Due to difficulties with cognitive flexibility (Hill, 2004; Hughes, 1998; Russo et al., 2007), central coherence (Frith, 1989; Frith & Happé, 1994), processing speed (Mayes & Calhoun, 2007; Travers et al., 2014), novelty processing, and the learning of new or complex behaviors (Maes, Eling, Wezenberg, Vissers, & Kan, 2011; Minshew & Goldstein, 1998), children with ASD might display some additional difficulties with the introduction of new mathematical material as compared to typically developing children, resulting in the maximum difference as illustrated in Figure 2. However, once the new material is integrated with previous knowledge and the children understand the new concepts, they can catch up with their typically developing peers. This implies that the peak or turning point of the graph has to be determined for each mathematical ability separately. The exact time point at which it occurs is not fixed, but will depend upon the introduction of new material specifically for the investigated mathematical components and can even recur at later stages. For example, *Chapter 4* demonstrated that the weakness in procedural calculation in first grade could not be observed anymore in second grade. This is probably because the procedural calculation exercises in second grade build upon those in first grade, of which the knowledge is then firmly established. In contrast, time-related competences were found to be a weakness in both first and third grade. This could be explained by the fact that the analog clock is introduced in first grade, resulting in complex new material because of the acquaintance with a new metric system. In second grade, children with ASD may get the opportunity to catch up with their typically developing peers, as no fundamentally new material is provided. In the third grade, however, the digital clock makes its introduction and children have to integrate this information with their previously acquired knowledge of the analog clock. This could again impose difficulties for children with ASD.

The suggestion of an interaction between autism-specific characteristics and age was previously reported by Goldstein et al. (1994). As such, we agree with these authors that the academic functioning of children with ASD may largely depend on the age at which the task is assessed. However, Goldstein et al. (1994) described early success and subsequent decline in the course of the academic functioning of children with ASD (with specific focus on complex information processing tasks). This is somehow consistent with the study of Wei, Lenz, and Blackorby (2013) who identified a slower growth in math in students with ASD, without an indication of catching up with their peers at later ages (Wei et al., 2013). In contrast, our results were interpreted in light of a combined cumulative growth – lag model. The differences in interpretation can be explained by several reasons. First of all, Goldstein et al. (1994) could not confirm their developmental pattern of early success and subsequent decline in performance for the field of mathematics, but only for the field of literacy. Second, differences are most likely (partly) due to the age range of the participants, as the median age of the individuals with ASD in the study of Goldstein et al. (1994) was 14 years. As a matter of fact, we can agree with Goldstein et al. (1994) that high-functioning children with ASD may perform well relative to peers as long as the task demands depend only on abilities that are within the developmental repertoire, and that task failure might only emerge when task demands exceed cognitive structures. Indeed, this line of reasoning can be applied to the results found in preschool (*Chapter 2* versus *Chapter 3*). Additionally, we agree that the final grades of elementary school (i.e., the age at which Goldstein et al. [1994] described a downturn in performance in children with ASD) would impose a higher difficulty level, possibly leading to a decline in scores. Because we only included participants up to grade 4, we were not able to determine such a pattern. Further longitudinal research is definitely needed to clear out these inconsistencies and to get a broad view on the academic functioning of children with ASD within a larger age range.

As a final remark on the discussion of the influence of autism-specific characteristics, one could point out the fact that almost no significant correlations were found between mathematical abilities and ASD characteristics. However, it should be noted that ASD characteristics were measured using the *Social Responsiveness Scale* (*SRS*; Roeyers, Thys, Druart, De Schryver, & Schittekatte, 2011), which puts its focus on social impairment. We hypothesize that when measures tapping for example the weaker drive for central coherence would have been used, we might have found more significant correlations with mathematical abilities.

The impact of socioeconomic status and age. Next to the remarks on the developmental perspective, also the sample characteristics warrant further discussion. *Chapter 4* and *Chapter 5* show some overlap in that they cover the same age group of first graders. Both studies compared the scores of children with ASD on procedural calculation, number fact retrieval, word/language problems, and time-related competences to the scores of the normed samples of the standardized tests. Figure 3 provides an overarching summary of the results of both studies. Shaded boxplots indicate that the mathematical abilities of children with ASD differ significantly from the normed population. Whenever the mathematical abilities of children with ASD differ significantly between the two studies, this is indicated by an asterisk.

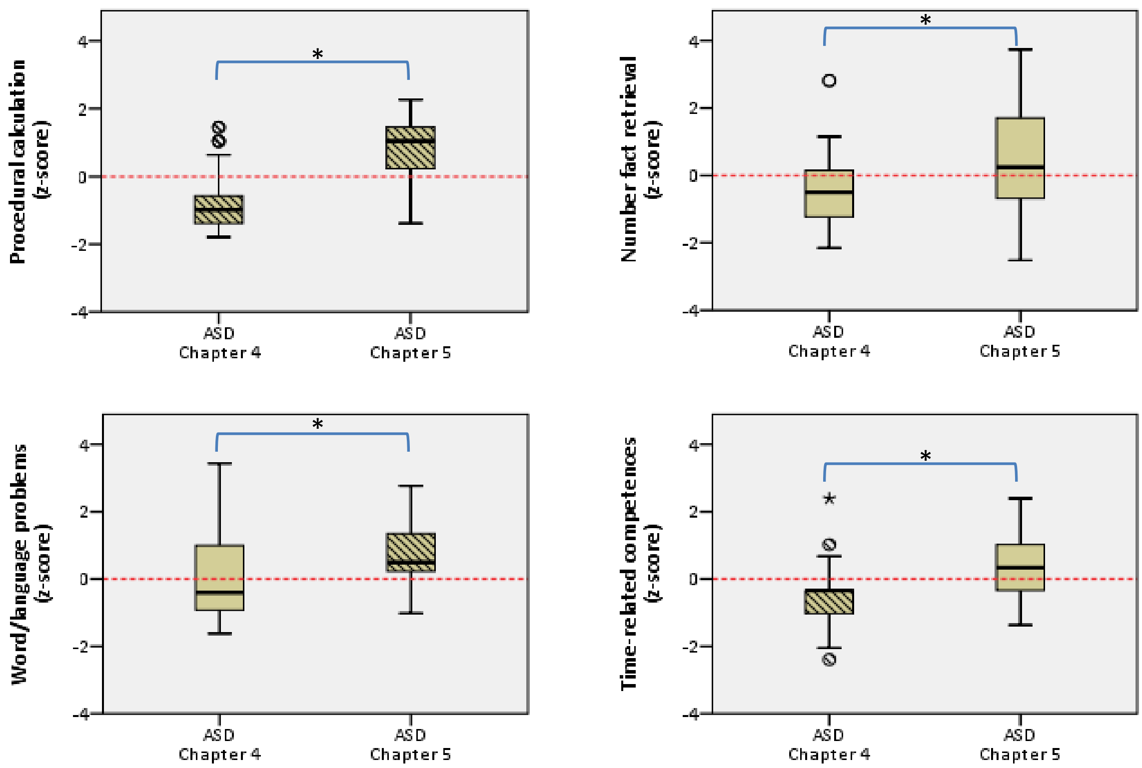

Figure 3. Performance of children with autism spectrum disorder (ASD) on the different domains of mathematics – Comparison between chapters.

Figure 3 illustrates that the ASD group in *Chapter 5* shows better mathematical abilities than the ASD group included in *Chapter 4*, for all four domains of mathematics. When examining the sample characteristics of both studies, two possible explanations emerge: the groups differ significantly on socioeconomic status (SES) and age (see Table 1). The hypothesis that children with a higher SES demonstrate higher mathematical abilities has already received support in previous literature: Parental social class and educational level, considered as proxy variables for SES (Aunio & Niemivierta, 2010), have proven to be predictive for mathematics achievement (N. C. Jordan & Levine, 2009; Schuchardt, Piekny, Grube, & Mahler, 2014). Parents with a high SES might be more engaged in the numerical development of their child, because of more (material) resources, education, and a higher personal level of understanding mathematics, but also by a certain attitude, interest, and locus of control toward numerical stimulation (Englund, Luckner, Whaley, & Egeland, 2004). Obviously, the difference between the two groups might also reflect the increase in mathematical knowledge with age, due to more specific formal schooling. Because the groups differ significantly on both aspects, it is not possible to disentangle the effect of both factors in our studies.

Table 1. *Sample characteristics of children with ASD in Chapter 4 and Chapter 5*

	ASD group - *Chapter 4* (n = 31)		ASD group - *Chapter 5* (n = 33)			
	M	*(SD)*	*M*	*(SD)*	Mann-Whitney U test	
SES[a]	40.29	(12.12)	47.03	(9.05)	U = 334.50	p = .017
SRS[b]	83.06	(30.31)	85.91	(30.97)	U = 485.00	p = .722
FSIQ[c]	102.67	(12.31)	105.38	(13.27)	U = 387.00	p = .493
Age	6.50	(0.24)	6.87	(0.29)	U = 153.50	p < .001

Note. ASD = children with autism spectrum disorder; [a]Socioeconomic status, [b]Raw score on the *Social Responsiveness Scale*, [c]Full scale IQ.

Being aware of the differences in SES and age between the ASD groups of the two chapters and the generally higher mathematical scores of children with ASD in *Chapter 5,* it is not surprising to find some differences in observed strengths or weaknesses between both groups of children with ASD when comparing them to the normed population (see Figure 3). The results from *Chapter 4* indicate a significant weakness on the domains of procedural calculation and time-related competences when comparing the children with ASD to the normed samples. In contrast, *Chapter 5* shows significant strengths on the domains of procedural calculation and word/language problems when comparing the children with ASD to the normed population. However, the overall difference in mathematical performance between the children of *Chapter 4* and *Chapter 5* may mask similar patterns of relative strengths or weaknesses in a specific domain of mathematics compared to the other domains. Therefore, it seems relevant to look at the relative position of the four domains of mathematics. In Figure 4, we can see a similar ranking of the domains of mathematics for both groups of children, except for procedural calculation. This might suggest that SES and age have its largest impact upon this domain of mathematics.

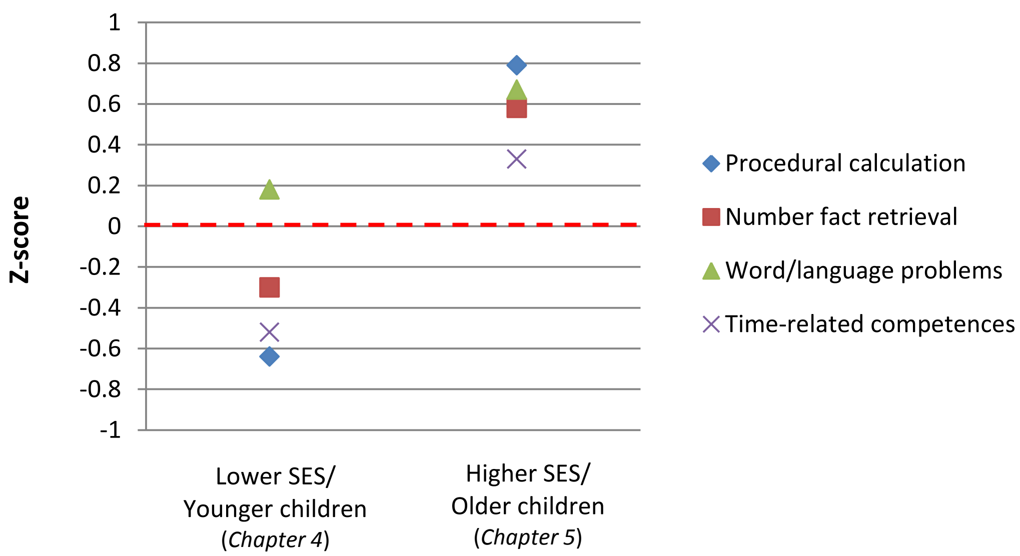

Figure 4. Relative order of the different domains of mathematics in children with autism spectrum disorder. *Note.* SES = socioeconomic status.

The fact that both groups of children obtained high scores on word/language problems is inconsistent with previous findings indicating that applied problems are relatively more complicated than calculation tasks (Wei, Christiano, Yu, Wagner, & Spiker, 2014) and the suggestion that reading comprehension deficits – characteristic for children with ASD (Ricketts, Jones, Happé, & Charman, 2013) – may impact negatively upon solving word/language problems (Whitby & Mancil, 2009). However, we should keep in mind that the exercises in our studies consisted of short and straightforward sentences (e.g., "1 more than 5 is __"), without the inclusion of irrelevant information (e.g., "Wanda has 47 cards. Willy has 9 cards less than Wanda and 2 cards more than Linda. How many cards does Willy have?"). It is possible that these kinds of exercises (i.e., with the inclusion of irrelevant information) with a higher level of difficulty would impose more problems for children with ASD, because they require more complex information processing (Noens & van Berckelaer-Onnes, 2005). Furthermore, as suggested by Frith and Happé (1996), it is also possible that difficulties with *theory of mind* (*ToM*; Frith, 1989) have led to a superior performance of children with ASD on word/language problems because of a smaller urgency to read the speaker's mind and, hence, less deceit for mathematical word/language problems.

The predictive value of early numerical competencies for first grade mathematics in children with autism spectrum disorder

Despite the previous mentioned findings on the comparison of early numerical competencies and mathematical abilities of children with ASD and typically developing children, it was nevertheless possible that children with ASD would show a different pattern of results when investigating the predictive value of early numerical competencies for first grade mathematics. It is for example likely that children with ASD use different strategies or cues when solving tasks (Gagnon et al., 2004; Iuculano et al., 2014; Jarrold & Russell, 1997), which may be, in turn, more related to their strategy use in later mathematics. This could result in different predictors or different predictive values for children with ASD and typically developing children, which was investigated in *Chapter 5*.

Although the predictive value of verbal subitizing (e.g., Reigosa-Crespo et al., 2012; Schleifer & Landerl, 2011), counting (e.g., Aunola et al., 2004; LeFevre et al., 2006), magnitude comparison (e.g., De Smedt et al., 2009; Landerl et al., 2004), estimation (e.g., Geary et al., 2008; Siegler & Booth, 2004), and arithmetic operations (e.g., Hanich et al., 2001; N. C. Jordan et al., 2010) for later mathematics performance in typically developing children and children with MLD has clearly been demonstrated before, surprisingly few studies have been conducted to explore the combined effect of early numerical competencies (Praet, Titeca, Ceulemans, & Desoete, 2013). In studies doing so, different early competencies have been suggested as strong(est) predictors: counting and logical abilities (e.g., Stock, Desoete, & Roeyers, 2010); counting, verbal subitizing, and magnitude comparison (Praet et al., 2013); or arithmetic operations (operationalized through number combinations and story problems; N. C. Jordan, Kaplan, Ramineni, & Locuniak, 2009). Partially in line with the study of Praet et al. (2013), we could confirm the important role of counting and verbal subitizing for later mathematics (*Chapter 5*). Again, we found the results of children with ASD to be highly similar to those of typically developing children, as both counting and verbal subitizing were predictive for later mathematical abilities in both groups of children. However, whereas counting was the strongest predictor in typically developing children, verbal subitizing was most predictive for mathematics in the ASD group (*Chapter 5*).

The finding that counting is a significant predictor of later mathematics is in line with an abundance of previous research demonstrating the pivotal role of this competency (Aunola et al., 2004; Desoete, Stock, Schepens, Baeyens, & Roeyers, 2009; Gersten, Jordan, & Flojo, 2005; Johansson, 2005; Le Corre, Van de Walle, Brannon, & Carey, 2006; Stock, Desoete, & Roeyers, 2009). The fact that we studied mathematical abilities in first graders as outcome may even have inflated this effect. Counting may be of particular importance in first grade, because children need counting procedures when acquiring the skills to solve procedural tasks and only favor memory-based retrieval of answers after increasingly efficient counting and decomposition strategies help them to establish associations in long-term memory (Fuchs et al., 2009; Johansson, 2005; Koponen, Aunola, Ahonen, & Nurmi, 2007).

Verbal subitizing has also been reported as a significant predictor for mathematics (e.g., Gray & Reeve, 2014; Landerl, 2013; Reigosa-Crespo et al., 2013; Reigosa-Crespo et al., 2012; Schleifer & Landerl, 2011). During an enumeration task, children have to make an association or translation between a nonverbal representation and a verbal label, or in other words, make a mapping of number words to preverbal magnitudes (Benoit, Lehalle, & Jouen, 2004; Gray & Reeve, 2014; Starkey & Cooper, 1995). The difference of such a verbal subitizing task with the other nonsymbolic tasks included in this dissertation lies in the fact that magnitude comparison and estimation require another ability, namely, the understanding of the numerical magnitude of the presented stimuli. This is a prerequisite for an accurate execution of the tasks, because they both involve a relative comparison of quantities (i.e., for the magnitude comparison task this consists of comparison of the first with the second dot pattern, for the estimation task this consists of comparison of the target stimulus with the anchors). In this sense, the verbal subitizing task shows some resemblance with a counting task: Both tasks involve the mapping of number words onto numerosities (without necessarily grasping the meaning of the numerosities). The results of *Chapter 5* suggest that this "mere" mapping between a verbal and nonsymbolic component is essential when trying to predict mathematical abilities in first grade.

Standardized regression coefficients revealed that verbal subitizing had a much stronger predictive value in the ASD group, however, the reason why this is the case remains unclear. Perhaps, due to the perceptual characteristics of an enumeration task (Benoit et al., 2004), this task might be more appealing to children with ASD, as they generally show enhanced perceptual functioning (Mottron, Dawson, Soulieres, Hubert, & Burack, 2006; Samson, Mottron, Soulieres, & Zeffiro, 2012). Another possibility is that there is more individual variation in the strategy used by children with ASD to solve this task (e.g., counting, subitizing, guessing …), whereas typically developing children show a more consistent strategy use (e.g., subitizing). This larger differentiation in processes or strategies might lead to a stronger predictive value for later mathematics achievement. However, future research is indispensable when trying to unravel the underlying causes of the current findings.

Finally, given the predictive value of verbal subitizing and counting for first grade mathematics performance in children with ASD, the observed trends toward weaker scores on verbal subitizing accuracy and conceptual counting knowledge in the third year of preschool (*Chapter 3*) are important to keep in mind. Given that the preschool time frame is a transitional period for children, these trends may be a predictor of concerns as children with ASD grow older.

STRENGTHS, LIMITATIONS, AND SUGGESTIONS FOR FUTURE RESEARCH

Several strengths, weaknesses, and ideas for future research have already been stipulated in the current and previous chapters of this dissertation. In the current section, the main limitations of this research project are summarized and some recommendations for future research are outlined.

Research on a behavioral level

In this doctoral dissertation, we intentionally chose for research on a behavioral level, trying to provide an exploratory analysis of possible differences in early numerical competencies or mathematical abilities between typically developing children and children with ASD. We took the view that, as practitioners' reports and research findings are not always confirming each other, this provides a valuable first step before focussing further on possible underlying mechanisms. However, it would be interesting to get further insights into the explanatory mechanisms behind some of the observed differences between children with ASD and typically developing children.

Given the findings from this doctoral research, it is rather unlikely that the reported difficulties in clinical practice and education could be explained from a MLD perspective. Indeed, if children with ASD would have a similar mathematical profile as children with MLD, they would in general have scored significantly lower than our typically developing children. The fact that this was not the case does, however, not preclude the observation that some children with ASD in our samples obtained a clinical score (more than 1.28 SD below average) on some domains of mathematics, meeting already one of the criteria (i.e., the severeness criterion) of MLD (American Psychiatric Association, 2013; Defour et al., 2004; Desoete et al., 2010; Fuchs et al., 2007). Future research should investigate this more thoroughly, for example, by comparing children with MLD to children with a comorbid diagnosis of ASD and MLD, meeting all three criteria of MLD (i.e., severeness criterion, resistance criterion, and mild exclusion criterion; Defour et al., 2004; Desoete et al., 2010; Fuchs et al., 2007). Such studies could investigate whether the comorbid group shows quantitavely more or more severe problems than the ASD- or MLD-only groups (cf. three independent disorders model; Pennington, 2006). Moreover, it could also be interesting to put the early numerical competencies and mathematical abilities of children with ASD alongside the performances of children with other clinical disorders in whom mathematical problems have been reported, such as children with Developmental Coordination Disorder (DCD; Pieters, Desoete, Van Waelvelde, Vanderswalmen, & Roeyers, 2012; Vuijk, Hartman, Mombarg, Scherder, & Visscher, 2011), Attention Deficit Hyperactivity Disorder (ADHD; Hart et al., 2010; Mayes, Calhoun, & Crowell, 2000) or reading disorder (Willcutt et al., 2013). It could be of particular interest to see whether the mathematical problems reported in these conditions share a same etiology or prove to be unique.

Returning to our findings, we strongly advocate the investigation of the role of autism-specific information processing characteristics on mathematical performance when conducting research on mathematical abilities in children with ASD on an explanatory level. Related to this topic, we also want to encourage research on mathematical processes (i.e., strategy use) in children with ASD, next to the focus on mathematical outcomes as was taken in this dissertation. Previous research indicated that children with ASD do use other strategies or processes to solve certain mathematical exercises (Gagnon et al., 2004; Iuculano et al., 2014). Extending the research in typically developing children or children with MLD (Baroody & Dowker, 2003; Kilpatrick, Swafford, & Findell, 2001; Torbeyns, Verschaffel, & Ghesquiere, 2004), one could further investigate the strategy use of children with ASD. Adaptive and flexible strategy use is known to be an important aspect of mathematical proficiency and adequate mathematical learning (Heinze, Star, & Verschaffel, 2009). Previous research demonstrated that children with MLD use different, less efficient or immature, strategies compared to typically developing children (Geary, 1993). As such, it could be meaningful to investigate which strategies children with ASD prefer, which could, in turn, lead to a better insight into their prevailing cognitive style. The research on strategy use has furthermore resulted in a debate on whether a variety and flexibility in strategy use is feasible, suitable, and favorable for children with MLD (e.g., Geary, 1993; Kilpatrick et al., 2001; Peters, De Smedt, Torbeyns, Verschaffel, & Ghesquiere, 2014; Verschaffel, Torbeyns, De Smedt, Luwel, & Van Dooren, 2007). Likewise, one could question which approach (development of mastery in only one strategy versus development of strategy variety and flexibility) is most beneficial for children with ASD to reach their full potential. Several methods, such as for example think-aloud protocols (Jacobse & Harskamp, 2012) or verbal self-reports (Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007; Peltenburg, van den Heuvel-Panhuizen, & Robitzsch, 2012), experimenter observation (Wu et al., 2008), choice/no-choice paradigms (Luwel, Onghena, Torbeyns, Schillemans, & Verschaffel, 2009), or nonverbal measures such as reaction times (Peters et al., 2014; Wu et al., 2008) can be used to shed light on this topic.

Sample characteristics

Several remarks can be made about the samples that were included in this dissertation. The first shortcoming in this context are the relatively small sample sizes that were used in the different empirical studies. Although this is a common feature of studies with clinical populations and our sample sizes are often comparable with those from similar previous studies (Chiang & Lin, 2007; Gagnon et al., 2004; Iuculano et al., 2014; Jarrold & Russell, 1997), replication of our results with larger samples is necessary. Indeed, small samples may lead to insufficient power, with a higher risk of type 2-errors. This might result in the false conclusion that there are no differences between groups, although – in reality – there are (Field, 2009).

Second, our samples – especially in *Chapters 2*, *3*, and *5* – had on average a relatively high SES, as measured with the *Hollingshead Four Factor Index* (Hollingshead, 1975). This index is based on the factors education, occupation, sex, and marital status (Hollingshead, 1975). Scores are classified into one of the following five ranges: 8-19, indicating low SES; 20-29, indicating lower middle SES; 30-39, indicating middle SES; 40-54, indicating upper middle SES; and 55-66, indicating high SES (Hollingshead, 1975). According to this classification, participants in this doctoral thesis (with means between

42.50 and 50.47 in the four empirical studies) fall, on average, into the upper middle group. A bulk of evidence suggests that individuals with a higher SES are more likely to participate in scientific research (e.g., Burg, Allred, & Sapp, 1997; Galea & Tracy, 2007; Hille et al., 2005), probably reflecting greater trust in science and a higher degree of volunteerism in this SES groups (Bak, 2001; Putnam, 1995). However, this sample selection bias puts limits to the generalizability of the findings to children with a lower socioeconomic background. As SES has also been identified as a correlate of mathematics performance (N. C. Jordan & Levine, 2009; Schuchardt et al., 2014; Wei et al., 2013), we could expect to observe more mathematical problems when investigating children with a lower SES.

Finally, we should keep in mind that only high-functioning children (with cut-off at IQ ≥ 80, in line with Mayes & Calhoun, 2003) were included in this dissertation. Because IQ is often found to correlate with mathematical abilities (e.g., Durand, Hulme, Larkin, & Snowling, 2005; Fuchs et al., 2006; Geary, 2011), a similar line of thought as in the previous paragraph on SES could be applied. Next to a generally lower performance on mathematics, it is also possible that a different pattern of strengths and weaknesses or different precursors would be found. Therefore, we cannot simply generalize the current results to lower functioning children with ASD. As such, research including lower functioning children and children with a lower SES could provide an added value to this budding research domain.

Type of study

When interpreting the results, it is important to bear in mind that the first three studies are cross-sectional in nature. As such, interpretations concerning developmental patterns within these chapters should be interpreted with care, and the findings need to be replicated in longitudinal research over longer time spans. *Chapter 5* contains a longitudinal study investigating the predictive value of early numerical competencies for first grade mathematics. Being the first in its kind, it provides a valuable onset for further research, which should also include measurements on autism-specific information processing characteristics, preferably relating the developmental pattern of these characteristics to the developmental pattern of mathematics. In addition, it would also be useful to incorporate additional background variables, for example to elucidate the effects of received therapy and guidance (e.g., content of the GON counseling) or the effects of instruction and learning packages on the mathematical development of children with ASD.

In addition, future research should – next to a between-group approach – also take a within-group perspective when investigating the early numerical competencies and mathematical abilities of children with ASD. This doctoral dissertation only lifted a little corner of the veil by showing no clear indications of subgroups in the plots of individual differences in *Chapter 4*. Since autism spectrum disorders, however, are known to be highly heterogeneous (e.g., Georgiades, Szatmari, & Boyle, 2013) – also in the field of academic functioning (e.g., Estes, Rivera, Bryan, Cali, & Dawson, 2011) – future research should continue to look for possible subgroups of children by conducting cluster analyses on larger groups of children. The examination of average group-level differences in a between-group approach may mask subgroups of individuals with remarkable poor or excellent skills (C. R. G. Jones et al., 2009; Wei et al., 2014). When conducting such research, we would advise not only to make analyses in an ASD group (e.g., C. R. G. Jones et al., 2009; Wei et al., 2014), but also to compare the variability of mathematical scores in this ASD group to that of a typically developing group of children. Such a comparison would enable us to determine whether certain subgroups are more or less prevalent in children with ASD than in typically developing peers.

IMPLICATIONS

Based on the conclusions of this doctoral dissertation, some important implications can be drawn. In the current section, research-related implications and practical implications are distinguished from each other and discussed subsequently.

Theoretical or research-related implications

Early numerical competencies in preschool. Developmental studies in the field of mathematics often focus on specific aspects or components when investigating early numerical competencies in preschool. Referring to the model of N. C. Jordan and Levine (2009) combining five important predictors of typical and atypical mathematical development (i.e., verbal subitizing, counting, magnitude comparison, estimation, and arithmetic operations), we can conclude that verbal subitizing and counting have the strongest value for predicting first grade mathematics (*Chapter 5*). As such, these two components are indispensable when conducting further longitudinal research on early predictors of mathematics, both in typically developing children and children with ASD.

We want to stress that our findings should not dilute the importance of the other early numerical competencies incorporated in the framework of N. C. Jordan and Levine (2009). After all, the predictive value of magnitude comparison (e.g., De Smedt et al., 2009; Landerl et al., 2004), estimation (e.g., Geary et al., 2008; Siegler & Booth, 2004), and arithmetic operations (e.g., Hanich et al., 2001; N. C. Jordan et al., 2010) has clearly been illustrated before. Rather, we want to demonstrate that it is worthwhile and recommended to adhere to a multicomponential approach to get a more comprehensive view on the typical and atypical mathematical development. This suggestion was recently endorsed by several authors (J. A. Jordan, Mulhern, & Wylie, 2009; Mazzocco, 2009; Simms, Cragg, Gilmore, Marlow, & Johnson, 2013). In fact, the use of a global composite score might mask strengths and weaknesses in the academic profile (Minshew et al., 1994). Given the shortage of research combining multiple early numerical competencies simultaneously into one model (Praet et al., 2013), the exact relations among the different early numerical competencies remain to be unveiled.

When further disentangling this information, it will be important to be aware of not only the constructs selected in a study, but also the operationalization of these constructs. One example is the use of symbolic versus nonsymbolic stimuli. Recently, divergent findings on the relationship between these two kinds of stimuli and mathematics achievement have been reported (see De Smedt, Noël, Gilmore, & Ansari, 2013 for a review). Correspondingly, *Chapter 3* indicates different patterns of results for the different presentation formats of the number line estimation task (i.e., visual Arabic format, auditory-verbal format, and analog magnitude format). Children with ASD and typically developing children showed a different underlying representation for the nonsymbolic format, whereas no differences were observable for the symbolic formats (cf. supra, Figure 1). As such, future research should consider all number representations as proposed by the *triple code model* (Dehaene, 1992) and be cautious when trying to generalize interpretations based on results obtained with one specific number representation, especially from nonsymbolic to symbolic stimuli or vice versa.

Mathematical abilities in elementary school. As different patterns of results were observed for the different domains of mathematics (*Chapter 4*), we can – just as for the preschool numerical competencies – confirm the importance of using a multicomponential approach when investigating mathematical abilities in elementary school. When taking the MLD literature as a starting point to put this multicomponential approach into practice, we could principally propose procedural calculation and number fact retrieval as two critical components to include in research. This is supported by evidence of a procedural and semantic memory subtype of MLD that has accumulated over the years (Geary, 1993, 2004; Mazzocco, Devlin, & McKenney, 2008; Pieters, Roeyers, Rosseel, Van Waelvelde, & Desoete, 2013; Temple, 1991). However, our findings indicated that the domains of word/language problems and time-related competences can also be of added value to include in research on the evaluation of strengths and weaknesses in mathematics in children with ASD (*Chapter 4*). Indeed, some significant strengths or weaknesses could be found on these two domains when comparing children with ASD to the normed samples. Together with the conclusion that, overall, children with ASD are more similar than different to typically developing children regarding their mathematics performance, this finding implies that research on the mathematical abilities of children with MLD cannot simply be extrapolated to children with ASD. Mathematical strengths and weaknesses in children with ASD might have their own specific character and cannot solely be explained from a MLD perspective (i.e., by focusing solely on the two subtypes of MLD that have received most scientific evidence in mathematics literature). This conclusion matches the statement of Minshew et al. (1994) that the psychoeducational profile of high-functioning children with ASD is different from that of typically developing children as well as distinct from the profile associated with prototypic learning disorders.

Due to this specific intrinsic character of mathematical abilities in children with ASD, it can be helpful to gain more insight into the mutual development of autism-specific information processing characteristics and mathematical performance. From a theoretical perspective, the WCC account (Frith, 1989) and the *executive dysfunction theory* (Ozonoff et al., 1991) seem to be good candidates to be investigated more thoroughly, because their possible influence on mathematics seems to be more obvious than for the ToM account (Baron-Cohen, Leslie, & Frith, 1985). Whereas the influence of the ToM account seems to be largely restricted to word/language problems including mental state terms, central coherence and executive functions seem to be involved in a wider array of mathematical abilities. A WCC can be linked to difficulties with conceptual knowledge, problems with understanding mathematical relations, impairments in generalizability, but also with assets in rote mathematical computation, systemizing, exact symbolic calculation, or calendrical calculation. Likewise, executive functions can play an important role in several exercises, such as keeping information in working memory when solving a math word problem or when recalling and applying math formulas; the organizational skills required to do step-by-step series of calculations; the ability to flexibly switch between procedures; or self-monitoring in order to check the effectiveness of your strategies in relation to the task demands and to assess the probability of an answer against an estimate.

Furthermore, when targeting the mathematical abilities of children with ASD, future research is challenged to take into account factors that can interact with these autism-specific information processing characteristics. Studying for example the mathematics curriculum, and knowing at which moments new complex material is introduced to the children, would enable us to set up new research investigating whether the assumption of a combined cumulative growth – lag model in children with ASD, as proposed earlier, holds. Setting up longitudinal research with multiple time points will be imperative to shed light on this developmental perspective. In addition, taking into account context variables, such as instruction and learning packages (e.g., Reusser, 2000), may further elucidate this theory because all of these factors may have their impact upon the supposed turning point of such a combined model. Previous research in Flanders found that 15% to 20% of the variance in mathematics performance could be attributed to variances in the school context (Ministry of the Flemish Community, 2004; Opdenakker & Van Damme, 2006). It is not inconceivable that such context factors are even of more influence in children with ASD, so theories on the development of mathematical abilities of children with ASD should involve the context in which the children learn, next to the individual characteristics and processes of the children.

Finally, our results of rather similar mathematical abilities in children with ASD and typically developing children are in contrast with the explicit demand of practitioners and teachers for adapted teaching methods on mathematics due to difficulties encountered by children with ASD (Department for Education and Skills, 2001; van Luit et al., 2006). In order to pinpoint the exact problems seen in clinical practice and, hence, to resolve the discrepancy between research and practice, it can be recommended to conduct qualitative research. Such a qualitative approach using in-depth interviews with practitioners and children with ASD can shed light on which kinds of problems are encountered by children with ASD and at which moment in mathematical development. Moreover, it can be used as an exploratory analysis to focus on frequently used processes and strategies, to set up an analysis of common errors seen in classroom, and to gain insight into the perception and experience of mathematics in children with ASD. Results gathered through qualitative research might guide further quantitative research.

We can conclude that research on mathematical abilities in children with ASD is still in its infancy (Fleury et al., 2014). The field demonstrates fragmentary and inconsistent results, due to different perspectives such as comorbidity studies (e.g., Mayes & Calhoun, 2006) versus within-group studies (e.g., C. R. G. Jones et al., 2009) or between-group studies (e.g., Iuculano et al., 2014); the different aspects investigated such as mathematical processes (e.g., Iuculano et al., 2014) versus mathematical outcomes (e.g., C. R. G. Jones et al., 2009); the different levels at which research is done such as the behavioral level (e.g., C. R. G. Jones et al., 2009) versus the neurobiological level (e.g., Iuculano et al., 2014); and the different age groups such as elementary school children (e.g., Iuculano et al., 2014) versus adolescents (e.g., Gagnon et al., 2004). More research is needed to replicate and especially integrate all these findings in order to understand the mathematical development of children with ASD more comprehensively.

Practical implications

Assessment. This dissertation demonstrates that children with ASD, on group level, mainly obtain average mathematical scores when compared to a normed sample (*Chapter 4*). This does, however, not detract from the fact that – just as in typically developing children – a lot of individual variation exists. As such, individual assessment and evaluation are always indicated. Based on the assumption of a developmental pathway (the combination of the cumulative growth model and the lag model; cf. supra), it will be important not only to focus on current outcomes, but also to closely monitor and evaluate the learning process of an individual child with ASD. Furthermore, studying the demands of the math curriculum can perhaps provide some additional clues on when to expect difficulties, which can then, in turn, be anticipated upon.

When trying to predict some of the variation in the mathematical abilities of high-functioning children with ASD, our results provide evidence that a test battery at preschool age should at least include a verbal subitizing task and a counting task (*Chapter 5*). Whether these two early numerical competencies maintain their predictive value beyond initial first grade mathematics remains a question for future research.

Education. The education of children with ASD is currently a hot topic in Flanders. The *M-decree* (Measures for pupils with specific educational needs; Flemish Ministry of Education and Training, 2014) wants to promote the inclusion of pupils with special educational needs in mainstream educational settings. In addition, a new *type 9* for children with ASD of average intelligence will be implemented in special education, for children who cannot, despite reasonable adjustments, properly be helped in mainstream educational settings (Flemish Ministry of Education and Training, 2014). The following sections describe the educational implications of the main findings of this dissertation, along with some reflections on the relations of these results to the M-decree.

The conclusion that, overall, high-functioning children with ASD and typically developing children are very alike with regard to their early numerical competencies and mathematical abilities is a valuable positive message, important to be communicated to parents and teachers. ASDs can influence many aspects of life, leading to a great family impact (Karst & Van Hecke, 2012) as well as to an impact upon academic functioning (Fleury et al., 2014). In this sense, it is reassuring for both parents and teachers to know that, in general, no additional concerns should be made about the early numerical competencies or mathematical abilities of high-functioning children with ASD. When focusing more specifically on mathematical abilities in elementary school, we found some weaknesses in first and third grade, whereas in fourth grade, only average abilities and strengths were found for children with ASD when compared to the normed samples (*Chapter 4*). This pattern of results could be suggestive of the fact that, when mathematical difficulties exist in children with ASD, they dissolve spontaneously with time (although longitudinal research taking into account all forms of guidance for the pupils with ASD is necessary to confirm this). As a consequence, no particular adaptations or interventions seem to be indicated. Regarding the M-decree, this line of thought would confirm and encourage the inclusion of high-functioning children with ASD in mainstream settings when only taking into account the field of mathematics. However, making this decision on the basis of mathematics performance only could be misleading. The whole academic and social functioning should be considered before expressing any views on this statement.

Although no adaptations seem indicated at first blush, we would like to emphasize our possible explanation for the observed weaknesses in the third year of preschool (*Chapter 3*) and in elementary school (*Chapter 4*), namely, the impact of autism-specific characteristics such as difficulties with conceptual knowledge (Minshew et al., 1994; Goldstein et al., 1996), cognitive flexibility (Hill, 2004; Hughes, 1998; Russo et al., 2007), central coherence (Frith, 1989; Frith & Happé, 1994), novelty processing, and the learning of new or complex behaviors (Maes et al., 2011; Minshew & Goldstein, 1998). Keeping this in mind, we should be aware that other aspects of mathematics could, at some time points, also prove to be difficult for children with ASD in an everyday class situation. It is possible that we did not measure these domains of mathematics or that we did not measure them at a pivotal moment (for example at the introduction of new or additional complex material). Considering this, we could still provide some tools to smooth the way for children with ASD to catch up more quickly and easily. Moreover, we could expect that such tools may not only have their impact on mathematics education but also on academic functioning in general.

First of all, children with ASD might benefit from explicit instruction when dealing with new material (Fleury et al., 2014). Such explicit instruction can be accomplished in several ways. Simply “stating the obvious” could for example be helpful for the mastery of the essential counting principals for children with ASD, because they might not grasp spontaneously what typically developing children implicitly learn from hands-on education. Next, sequencing different steps or processes to complete a task can be advantageous to overcome executive function deficits. Whitby (2013), for example, already demonstrated that cognitive and metacognitive strategies can be successfully used to improve word problem solving abilities of individuals with ASD. In addition, visual support can be used in the context of a weaker central coherence, in order to facilitate the connection of important ideas (Fleury et al., 2014). One might for example try to visualize how splitting numbers and addition/subtracting by regrouping exercises are related to each other to enhance procedural calculation skills. Furthermore, since children with ASD are known to have difficulties with generalizing skills beyond the immediate teaching context (National Research Council, 2001), it is advised to provide enough opportunities to practice and apply learned skills across different settings (Fleury et al., 2014).

To summarize, in our opinion, it will be important to attune the instructional strategies on mathematics to the unique learning and cognitive style of children with ASD in order to optimize their mathematical learning and, hence, performance. In doing so, many types of interventions are supposedly helpful for all students, which brings us to the concept of *universal design for learning* (*UDL*). A UDL framework aims at creating learning environments and adopting teaching materials and practices that allow for participation by all children, regardless of individual learning differences (Hanna, 2005). As such, UDL principles lend themselves to implement inclusionary practices in general educational settings, because they consist of flexible approaches that can be customized and adjusted for individual needs (Hitchcock, Meyer, Rose, & Jackson, 2002). In such a design, all children get enough time with a daily relooping of previous learning material and an explicit vocabulary building. As such, children with ASD do not have to depend on implicit learning, but all children benefit from the adjusted speed and adequate support of mathematics. As the abovementioned suggestions fit well within this approach, we encourage its further development, implementation, and evaluation. The M-decree can help to provide a statutory framework to do this.

CONCLUSION

Since mathematics is a largely uncharted research domain in children with ASD, providing more insight into the early numerical competencies and mathematical abilities of children with ASD was the starting point of this doctoral research. Overall, we can conclude that the early numerical competencies and mathematical abilities of high-functioning children with ASD are far more similar than different to those of their typically developing peers. Based on our findings, we would recommend to create learning environments and to use teaching materials that raise possibilities for all students, such as conceptualized within the UDL framework. With regard to the prediction of first grade mathematics in children with ASD, counting and especially verbal subitizing should, given their substantial predictive value, be included in the assessment at preschool level. Although this doctoral dissertation extends the limited information available on the mathematical abilities of children with ASD, many questions remain unanswered. Therefore, we encourage future research to take further steps in unraveling this complex puzzle by integrating different perspectives in order to optimize the learning environment of children with ASD.

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NEDERLANDSTALIGE SAMENVATTING

Autismespectrumstoornis (*ASS*) wordt gekenmerkt door deficiënties in de sociale communicatie en sociale interactie, die gepaard gaan met restrictieve en repetitieve gedragspatronen, interesses of activiteiten (American Psychiatric Association [APA], 2013).

De afgelopen decennia kon worden vastgesteld dat een toenemende groep kinderen met een ASS een schoolloopbaan in het reguliere onderwijs probeert te doorlopen (Adreon & Durocher, 2007; Fleury et al., 2014; Smith, 2012). Dit heeft op zijn beurt geleid tot een toegenomen interesse in het cognitieve en academische functioneren van deze groep kinderen. Gezien de bezorgdheden omtrent de rekenvaardigheden van kinderen met een ASS die vanuit het praktijkveld rijzen (Department for Education and Skills, 2001; van Luit, Caspers, & Karelse, 2006), vormt het rekendomein een relevant onderzoeksonderwerp. Ook vanuit autisme-specifieke verklaringsmodellen – zoals de *'theory of mind' hypothese* (Baron-Cohen, Leslie, & Frith, 1985), de *theorie van de zwakke centrale coherentie* (Frith, 1989) en de *theorie van de executieve disfunctie* (Ozonoff, Pennington, & Rogers, 1991) – zou men een impact kunnen verwachten van cognitieve kenmerken op het schools functioneren van kinderen met een ASS (Fleury et al., 2014; Pellicano, Maybery, Durkin, & Maley, 2006). Ondanks deze veronderstelde link tussen autisme-specifieke karakteristieken en rekenen, de bezorgdheden en de groeiende vraag naar een aangepaste rekenmethodiek voor kinderen met een ASS, werd er in de literatuur tot op heden relatief weinig aandacht besteed aan de rekenprofielen van kinderen met een ASS.

Anekdotisch en beschrijvend onderzoek suggereert dat heel wat individuen met een ASS uitblinken in rekenen. Studies van Baron-Cohen en collega's (Baron-Cohen, Wheelwright, Burtenshaw, & Hobson, 2007; Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001) tonen aan dat wiskundigen een hogere score behalen op vragenlijsten die peilen naar ASS-gerelateerde kenmerken en dat ASS drie- tot zevenmaal vaker voorkomt bij wiskundigen. Verschillende gevalstudies sluiten hierbij aan en rapporteren bijvoorbeeld opmerkelijke sterktes in exacte berekeningen bij personen met een ASS (Gonzalez-Garrido, Ruiz-Sandoval, Gomez-Velazquez, de Alba, & Villasenor-Cabrera, 2002; Sacks, 1986; Smith 1983).

Wanneer we de empirische studies in beschouwing nemen, zien we echter dat het schaarse onderzoek dat reeds werd uitgevoerd, focust op uiteenlopende aspecten en – mede door deze diversiteit in focus – inconsistente resultaten oplevert. In wat volgt geven we een overzicht van deze bevindingen. Ten eerste blijkt uit comorbiditeitsonderzoek dat het voorkomen van rekenstoornissen bij kinderen met een ASS (variërend tussen 12% en 46%; Mayes & Calhoun, 2006; Reitzel & Szatmari, 2003) beduidend hoger ligt dan de geschatte prevalentie van rekenstoornissen bij de algemene schoolgaande populatie (variërend van 2% tot 14%; Barbaresi, Katusic, Colligan, Weaver, & Jacobsen, 2005; Desoete, Roeyers, & De Clercq, 2004; Geary, 2011). Daarnaast zien we studies met een focus op interindividuele verschillen, waarin twee onderzoekslijnen zitten vervat. Binnen de onderzoekslijn omtrent rekenproducten rapporteren sommige studies dat kinderen met een ASS gelijkaardige of zelfs betere rekenuitkomsten behalen ten opzichte van typisch ontwikkelende kinderen (Chiang & Lin, 2007; Gagnon, Mottron, Bherer, & Joanette, 2004; Iuculano et al., 2014), terwijl andere studies suggereren dat kinderen met een ASS significant lager presteren op rekentaken in vergelijking met de algemene populatie (Wei, Christiano, Yu, Wagner, & Spiker, 2014; Wei, Lenz, & Blackorby, 2013). Binnen de onderzoekslijn omtrent rekenprocessen wordt globaal gevonden dat kinderen met een ASS andere rekenprocessen of strategieën gebruiken dan typisch ontwikkelende kinderen (Gagnon et al., 2004; Iuculano et al., 2014; Jarrold & Russell, 1997). Een laatste groep studies, de studies die inzoomen op intra-individuele profielen, gaat na hoe de rekenvaardigheden van kinderen met ASS zich verhouden ten opzichte van andere cognitieve domeinen. Ondanks het feit dat de meeste kinderen rekenscores behalen die in lijn liggen van hun algemene cognitieve functioneren, blijkt toch een substantieel aandeel van de kinderen een relatieve sterkte of zwakte te vertonen voor rekenen (Jones et al., 2009; Mayes & Calhoun, 2003). Tot op heden is er echter nog geen uitsluitsel over welke subgroep (i.e., de subgroep van kinderen met een relatieve sterkte voor rekenen of de subgroep van kinderen met een relatieve zwakte voor rekenen) de grootste groep vormt bij kinderen met een ASS.

DOEL VAN HET DOCTORAATSONDERZOEK

De bezorgheden omtrent de rekenvaardigheden van kinderen met een ASS (Department for Education and Skills, 2001; van Luit et al., 2006) die vanuit de praktijk worden geopperd, werden tot op heden niet vertaald in de hoeveelheid onderzoek in dit domein. Dit doctoraatsonderzoek wil dan ook bijdragen tot een beter inzicht in het rekenen van een groep hoogfunctionerende kinderen met een ASS. Hiertoe werden de vroeg-numerieke competenties en de rekenvaardigheden van kinderen met een ASS vergeleken met de resultaten van typisch ontwikkelende kinderen. Met deze verkennende analyse op gedragsniveau wilden we de inconsistente onderzoeksresultaten helpen ontrafelen en de hulpverleners, ouders en leerkrachten ondersteunen in hun zoektocht naar antwoorden.

Hiertoe werden in dit doctoraatsonderzoek drie meer specifieke onderzoeksdoelen vooropgesteld. Een eerste doel betrof het vergelijken van vijf *vroeg-numerieke competenties* van kinderen met een ASS en typisch ontwikkelende kinderen in de kleuterklas. In eerste instantie werd dit onderzocht op een tijdstip waarop nog weinig expliciete aandacht wordt besteed aan getallen in het Vlaamse leerplan, met name de tweede kleuterklas. Vervolgens werd dezelfde onderzoeksvraag gesteld op een moment waarop getallen in toenemende mate geïntegreerd worden in het curriculum, ter voorbereiding voor de start in de lagere school, met name de derde kleuterklas. Volgende vijf vroeg-numerieke competenties werden onderzocht: (1) *verbaal subitizeren*: de vaardigheid om kleine aantallen snel en accuraat te benoemen (Kaufman, Lord, Reese, & Volkmann, 1949), (2) *tellen*: kennis van de telrij (procedurele kennis) en van de telprincipes (conceptuele kennis; LeFevre et al., 2006), (3) *groottevergelijking*: de vaardigheid om twee hoeveelheden te onderscheiden van elkaar teneinde de grootste van beide aan te duiden (Gersten et al., 2012), (4) *schatten*: de vaardigheid om getallen of aantallen op een getallenas te situeren (Siegler & Opfer, 2003), en (5) *rekenoperaties*: de vaardigheid om eenvoudige optel- en aftrekoefeningen op te lossen (Purpura, Hume, Sims, & Lonigan, 2011). Een tweede doel bestond erin de vaardigheden op vier *rekendomeinen in de lagere school* te vergelijken tussen kinderen met een ASS en typisch ontwikkelende kinderen. Meer specifiek werden volgende vier rekendomeinen onderzocht: (1) *procedurele vaardigheden*: rekenprocedures kunnen uitvoeren door een algoritme te gebruiken (Dowker, 2005), (2) *geautomatiseerde rekenfeiten*: het automatisch oproepen van basisrekenfeiten (optellingen, aftrekkingen, tafels) die in het langetermijngeheugen opgeslagen werden (Dowker, 2005), (3) *rekentaal*: talige en contextrijke opgaven (vraagstukken) kunnen oplossen (Geary, 2000), en (4) *tijdscompetentie*: het oplossen van opgaven met betrekking tot het meten en vaststellen van tijd, zoals kloklezen, kalendergebruik en tijdsintervallen (Burny, Valcke, & Desoete, 2009). Als laatste werd de predictieve waarde van vijf vroeg-numerieke competenties op kleuterleeftijd (derde kleuterklas) voor de rekendomeinen in de lagere school (eerste leerjaar) onderzocht. Hierbij werden de voorspellende verbanden bij kinderen met een ASS en typisch ontwikkelende kinderen opnieuw met elkaar vergeleken.

VOORNAAMSTE ONDERZOEKSRESULTATEN

Wat de vroeg-numerieke competenties betreft, werden geen significante verschillen vastgesteld tussen kinderen met een ASS en typisch ontwikkelende kinderen in de tweede kleuterklas (*Hoofdstuk 2*). Dit wijst op een gelijkaardige getalverwerking en basis voor het latere rekenen bij kinderen met en zonder een ASS op een moment waarop weinig aandacht wordt besteed aan getallen in het Vlaamse leerplan.

De bevindingen van de derde kleuterklas – een moment waarop cijfers aan belang winnen in het leerplan in het kader van de overgang naar de lagere school – sluiten hierbij aan, gezien opnieuw geen significante verschillen konden worden gevonden tussen beide groepen kinderen (*Hoofdstuk 3*). Ondanks deze algemene gelijkenissen, werden echter wel enkele marginaal significante resultaten vastgesteld. Kinderen met een ASS vertoonden hierbij een iets lagere score (trend) op verbaal subitizeren (accuraatheid) en op conceptuele kennis van het tellen (*Hoofdstuk 3*). Bij het schatten op een getallenas vertoonden kinderen met een ASS ook een zwakkere representatie voor stippenpatronen dan de typisch ontwikkelende kinderen (*Hoofdstuk 3*). Dit wijst erop dat de getalrepresentatie voor het schatten van stippenpatronen minder goed is ontwikkeld bij kinderen met een ASS in vergelijking met leeftijdsgenoten.

Wat de rekenvaardigheden in de lagere school betreft, werd een patroon van zowel sterktes, gemiddelde scores, als zwaktes geobserveerd bij hoogfunctionerende kinderen met een ASS (die regulier onderwijs volgden) in vergelijking met een normgroep van leeftijdsgenoten (*Hoofdstuk 4*). Kinderen met een ASS vertoonden een sterkte op rekentaal in het tweede en vierde leerjaar. Er was echter ook evidentie voor een zwakte op procedurele vaardigheden in het eerste leerjaar en een zwakke tijdscompetentie in het eerste en het derde leerjaar. In alle andere gevallen werden gemiddelde scores geobserveerd ten opzichte van de normgroepen (*Hoofdstuk 4*). Deze dataset suggereert een ontwikkelingspatroon waarbij kinderen met een ASS voornamelijk moeilijkheden vertonen met de introductie van nieuw rekenmateriaal. Zo worden bij de procedurele vaardigheden (het leren optellen en aftrekken) vooral hoge eisen gesteld in het eerste leerjaar, waarin splitsingen en brugoefeningen voor het eerst worden geïntroduceerd (Vlaams Ministerie van Onderwijs en Vorming, 2014a). De volgende leerjaren doen veeleer beroep op een extrapolatie en toepassing van deze kennis naar grotere getallen. Wat tijdscompetentie betreft, zien we een grote hoeveelheid nieuw materiaal in het eerste leerjaar. Er wordt dan immers een compleet nieuw metrisch systeem aangeleerd en kinderen maken voor het eerst kennis met de analoge klok, die tot op het uur en half uur moet kunnen worden gelezen (Vlaams Ministerie van Onderwijs en Vorming, 2014a). In het tweede leerjaar komt weinig nieuw materiaal aan bod; de kennis wordt uitgebreid naar het lezen van de klok tot op het kwartier. In het derde leerjaar dient echter de kennis van de analoge klok te worden aangevuld met de digitale klok en moet de klok tot op de minuut correct kunnen worden gelezen (Vlaams Ministerie van Onderwijs en Vorming, 2014a). Dit doctoraatsonderzoek biedt enige evidentie voor het feit dat kinderen met een ASS net op deze overgangsmomenten een zwakkere score behalen in vergelijking met hun typisch ontwikkelende leeftijdsgenoten. Kinderen met een ASS lijken trager te zijn in het vatten van impliciete instructies die hun leeftijdsgenoten intuïtief en spontaan lijken te begrijpen. Eenmaal ze echter de techniek onder de knie hebben en de instructie hebben begrepen, lijken deze kinderen wel even vlot te kunnen rekenen als hun leeftijdsgenootjes.

Wat de voorspellende waarde van vroeg-numerieke competenties voor het rekenen in de lagere school betreft, bleken vooral verbaal subitizeren en tellen belangrijke predictoren te zijn, dit zowel bij kinderen met een ASS als bij typisch ontwikkelende kinderen (Titeca, Roeyers, Josephy, Ceulemans, & Desoete, 2014). Waar tellen de beste voorspeller was bij typisch ontwikkelende kinderen, was verbaal subitizeren echter meer voorspellend bij kinderen met een ASS. Na controle voor IQ bleek tellen voornamelijk voorspellend voor de procedurele vaardigheden in het eerste leerjaar (Titeca et al., 2014). Dit is niet verwonderlijk, aangezien kinderen vooral telprocedures gebruiken om dergelijke taken (optellen en aftrekken tot 20) tot een goed einde te brengen (Fuchs et al., 2009; Johansson, 2005; Koponen, Aunola, Ahonen, & Nurmi, 2007). Ook verbaal subitizeren bleek een grote voorspellende waarde te hebben voor de rekenvaardigheden in het eerste leerjaar, vooral bij kinderen met een ASS. Dit lijkt erop te wijzen dat de 'mapping' of translatie tussen een symbolische (getalwoord) en een non-symbolische (hoeveelheid stippen) getalrepresentatie (Benoit, Lehalle, & Jouen, 2004; Gray & Reeve, 2014) essentieel is om rekenvaardigheden te voorspellen. Het feit dat dit in grotere mate geldt voor kinderen met een ASS kan gelegen zijn aan een sterker perceptueel functioneren (Mottron, Dawson, Soulieres, Hubert, & Burack, 2006; Samson, Mottron, Soulieres, & Zeffiro, 2012) of een grotere variatie in strategiegebruik bij kinderen met een ASS. Toekomstig onderzoek dient dit echter verder uit te diepen.

PRAKTISCHE IMPLICATIES

Dit doctoraatsonderzoek toont aan dat hoogfunctionerende kinderen met een ASS op groepsniveau vooral gelijkenissen vertonen met typisch ontwikkelende kinderen voor wat hun vroeg-numerieke competenties en rekenvaardigheden betreft. Dit lijkt ons een waardevolle en positieve boodschap om naar ouders en leerkrachten toe te communiceren. Aangezien ASS een grote invloed kan uitoefenen op diverse levensdomeinen en ook een grote impact heeft op het gezinsleven (Karst & Van Hecke, 2012), kan het voor ouders van hoogfunctionerende kinderen met een ASS geruststellend zijn om te weten dat zij zich over het algemeen geen bijkomende zorgen hoeven te maken omtrent het leren rekenen van hun kind.

Wanneer we de resultaten van de lagereschoolkinderen met een ASS nader onder de loep nemen, wordt gesuggereerd (i.e., longitudinaal onderzoek is nodig om deze evolutie te bevestigen) dat de zwaktes die aanwezig zijn tijdens het eerste en het derde leerjaar (telkens wanneer er nieuwe en/of complexe leerstof aangebracht wordt), spontaan lijken te verdwijnen in de loop van het vierde leerjaar. Dit wekt opnieuw de indruk dat geen grootschalige reken-gerelateerde aanpassingen aan handboeken of interventies op het vlak van rekenen zijn aangewezen voor alle kinderen met een ASS. Bovenstaande bevindingen passen in het gedachtegoed van het recent geformuleerde *M-decreet* (Vlaams Ministerie van Onderwijs en Vorming, 2014b), waarmee men inclusie van leerlingen met specifieke onderwijsbehoeften binnen het reguliere onderwijs tracht te bevorderen. Hierbij dient echter te worden opgemerkt dat een beslissing 'voor inclusief onderwijs' nooit kan worden gebaseerd op de diagnostiek van één enkel academisch domein. Zowel het volledige academische en sociale functioneren, alsook de levenskwaliteit van kinderen met een ASS dient te worden in rekening gebracht om hieromtrent een gegrond standpunt te kunnen innemen.

Ondanks de bevinding dat kinderen met een ASS in veel opzichten gelijkaardig functioneren aan typisch ontwikkelende kinderen voor wat betreft rekenen, kunnen we echter niet voorbijgaan aan enkele verschillen die tijdens dit onderzoeksproject zijn naar voor gekomen. Zowel in de derde kleuterklas als tijdens de lagere school werd vastgesteld dat kinderen met een ASS op bepaalde onderdelen van het rekenen (marginaal) significant zwakker scoren dan hun typisch ontwikkelende leeftijdsgenoten. Toekomstig onderzoek zal moeten uitwijzen of autisme-specifieke informatie-verwerkingskarakteristieken zoals moeilijkheden met cognitieve flexibiliteit (Hill, 2004; Hughes, 1998; Russo et al., 2007), verwerking van nieuwe stimuli (Maes, Eling, Wezenberg, Vissers, & Kan, 2011) of het leren van nieuw of complex gedrag (Minshew & Goldstein, 1998; Minshew, Goldstein, Taylor, & Siegel, 1994) hun rol spelen bij de zwakkere prestaties van kinderen met een ASS. In dit opzicht kunnen we met enige voorzichtigheid enkele aanbevelingen formuleren om de aanpak van kinderen met een ASS zoveel mogelijk te optimaliseren. Deze handvatten kunnen bovendien niet enkel een bijdrage leveren voor het rekendomein, maar bieden ook de mogelijkheid het algemene academische functioneren op een positieve manier te beïnvloeden. Ten eerste kunnen kinderen met een ASS een voordeel halen uit het voorzien van expliciete instructies bij het aanbieden van nieuw of complex materiaal (Fleury et al., 2014). Concreet kan hierbij worden gedacht aan het opsplitsen van taken in meer omvatbare deelstappen of het voorzien van adequate visuele ondersteuning. Verder lijkt het ook belangrijk om voldoende leergelegenheden en toepassingen te voorzien, teneinde een generalisering van de aangeleerde vaardigheden te bevorderen (Fleury et al., 2014). Kort samengevat pleit dit doctoraatsonderzoek voor een optimale afstemming van de instructiestrategieën op de unieke leerstijl en cognitieve stijl die eigen is aan kinderen met een ASS indien men hun rekenontwikkeling zo goed mogelijk wil bevorderen. Veel van deze aanbevelingen zijn echter nuttig voor alle leerlingen. Het *Universal Design for Learning (UDL)* lijkt dan ook een passend kader waarbinnen deze aanpassingen kunnen worden voorzien. Binnen dit kader wordt gestreefd naar het creëren van leeromgevingen, leermaterialen en didactische benaderingen die nuttig kunnen zijn voor alle kinderen, ongeacht de individuele verschillen in leerachtergronden (Hanna, 2005). Het UDL-gedachtegoed leent zich er ons inziens dan ook toe om inclusie binnen het reguliere onderwijs te implementeren (Hitchcock, Meyer, Rose, & Jackson, 2002). Het M-decreet kan hierbij een wettelijk kader vormen om deze visie te ondersteunen en te evalueren.

Wat assessment en behandeling van kinderen met een ASS betreft, maakt dit doctoraatsonderzoek duidelijk dat vooral het verbaal subitizeren en tellen op kleuterleeftijd belangrijke predictoren zijn voor de latere rekenvaardigheden (Titeca et al., 2014). Een benoemtaak en een teltaak vormen dan ook onontbeerlijke onderdelen van een testbatterij om de variatie in de rekenvaardigheden van hoogfunctionerende kinderen met een ASS te voorspellen. Bij het evalueren van de rekenvaardigheden in de kleuterklas of in de lagere school, lijkt het verder aangewezen om een multi-componentiële benadering te hanteren. Dit doctoraatsonderzoek biedt immers evidentie voor het feit dat kinderen met een ASS een differentieel rekenpatroon vertonen en dus niet op alle rekendomeinen even sterk of zwak zijn. Zich beperken tot het evalueren van één rekendomein of het hanteren van één composietscore kan aldus misleidende resultaten opleveren. Tot slot wensen we te benadrukken dat, net als bij typisch ontwikkelende kinderen, een grote individuele variatie bestaat in de rekenvaardigheden van kinderen met een ASS. Daarom is het aanbevolen om steeds een individuele assessment uit te voeren en ook het individuele leerrendement en de vooruitgang op de diverse rekendomeinen van de leerling op te volgen.

CONCLUSIE

Onderzoek naar de rekenvaardigheden van kinderen met een ASS staat momenteel in zijn kinderschoenen. Het huidige doctoraatsonderzoek heeft dan ook vanuit een verkennende analyse op gedragsniveau meer inzicht gebracht in de vroeg-numerieke competenties en rekenvaardigheden van kinderen met een ASS. De resultaten van dit onderzoeksproject toonden aan dat de rekenvaardigheden van hoogfunctionerende kinderen met een ASS vrij gelijk zijn aan deze van typisch ontwikkelende leeftijdsgenoten. Anderzijds kon ook vastgesteld worden dat kinderen met een ASS meer moeite lijken te hebben met het aanbieden van nieuwe of complexe leerstof en dat verbaal subitizeren in de kleuterklas een sterkere voorspeller vormt voor latere rekenvaardigheden dan bij typisch ontwikkelende kinderen. Met dit doctoraatsonderzoek hopen we een eerste aanzet te hebben gegeven om de vragen vanuit het werkveld naar de noodzaak van een specifieke rekendidactiek te beantwoorden. We hopen dat toekomstig onderzoek deze ingeslagen weg verder kan vervolgen om het inzicht in de rekenontwikkeling van kinderen met ASS nog te verruimen, teneinde de leeromgeving van deze kinderen verder te optimaliseren.

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