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Early Numerical Competencies in 5- and 6-Year-Old Children with Autism Spectrum Disorder

Early Education and Development

Abstract

Research Findings: 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 onwards, with little attention for possible precursors at younger ages. The current exploratory 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. *Practice or Policy:* 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 in this study. However, some downward trends in mathematics performance were identified in children with ASD, which can serve as basis for additional research in this field.

Keywords: mathematics; early numerical competencies; preschool; autism spectrum disorder

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 of these children are included in general education settings and make the transition to college (Adreon & Durocher, 2007). Despite being high-functioning, these children often struggle in 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; 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 an important developmental period to focus on in mathematics research. Indeed, understanding the learning trajectories of mathematics can help us to identify the relevant mathematical goals along with the appropriate tasks or instructional activities to support children in their learning (Clements & Sarama, 2009). Previous studies have identified several key precursors of mathematics, which have been summarized into the framework of N. C. Jordan and Levine (2009). Each component, along with its significance for later math performance, will be discussed below.

Verbal subitizing is the ability to rapidly and accurately assess small quantities of up to three (or four) items (Kaufman, Lord, Reese, & Volkmann, 1949). Various studies demonstrated its importance for mathematical development (Landerl, Bevan, & Butterworth, 2004; Traff, 2013), over and above domain-general abilities (Gray & Reeve, 2014; 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). Counting is an important predictor of later mathematics (e.g., Aunola, Leskinen, Lerkkanen, & Nurmi, 2004). Whereas procedural counting knowledge is predictive for numerical facility, conceptual counting knowledge is predictive for untimed mathematical achievement (Desoete, Stock, Schepens, Baeyens, & Roeyers, 2009). *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, Gobel, Moll, Smets, & Reynvoet, 2013) and non-symbolic (Halberda, Mazzocco, & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2013), 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). Number-space mapping is important for mathematical ability: Both the linearity of number line judgments (Ashcraft & Moore, 2012; Siegler & Booth, 2004) and the estimation accuracy (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 have proven to be predictive for later applied problem solving (N. C. Jordan, Glutting, & Ramineni, 2010).

Early numerical competencies have not only be related to typical, but also to atypical mathematical development. Children with a mathematical learning disorder (MLD) seem to 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), number line 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 and colleagues demonstrated for example a three- to sevenfold increase for ASDs among mathematicians (Baron-Cohen, Wheelwright, Burtenshaw, & Hobson, 2007) and anecdotal case studies provided evidence of superior calculation, quantification, and memorization of mathematical patterns in individuals with ASD (Sacks, 1986; Smith 1983; Treffert, 2000).

In addition, based on the three major cognitive theories of ASD (Rajendran & Mitchell, 2007), divergent predictions on how children with ASD will perform on mathematics can be assumed. Nevertheless, research connecting this topic with mathematics performance is scarce to date. The impact of the *theory of mind hypothesis* (ToM; Baron-Cohen, Leslie, & Frith, 1985) can assumed to be largely restricted to mathematical word problems involving mental state terms because of a smaller urgency to read the speaker's mind (Frith & Happe, 1996), but also a weaker performance in exercises urging a correct use of mental state terms. The *theory of executive dysfunction* (ED; Ozonoff, Pennington, & Rogers, 1991) has not yet been related to mathematical functioning in children with ASD, but since one of the aetiological cognitive factors supposedly contributing to MLD constitutes of deficits in executive functions (e.g., Andersson & Ostergren, 2012; Geary, Hoard, & Bailey, 2012), one might also expect to observe mathematical problems in children with ASD. Finally, the *weak central coherence theory* (WCC; Frith, 1989) has already been linked to verbal subitizing in children with ASD and research data point in the direction of the use of a serial counting strategy rather than a subitizing process to enumerate small quantities in children with ASD (Gagnon, Mottron, Bherer, & Joanette, 2004; Jarrold & Russell, 1997).

Moreover, it has been argued – but not yet demonstrated for the field of mathematics – that children with ASD show preserved procedural and mechanical skills, but impaired complex information processing abilities (e.g., Goldstein, Minshew, & Siegel, 1994), which has later been linked to the WCC framework (Noens & van Berckelaer-Onnes, 2005). We can conclude that these largely unexplored hypotheses highlight the need for empirical research on this topic. Although explanatory research investigating the impact of autism-specific cognitive characteristics would be of great interest, it seems first of all mandatory to evaluate if children with ASD score significantly different from TD peers altogether. To date, research evaluating this topic is not only scarce, but it also leaves us with inconclusive results.

First, some studies suggest a *weakness* for mathematics in children with ASD. Comorbidity studies demonstrated higher comorbidity rates of MLD and ASD in children aged 6-16 years (Mayes & Calhoun, 2006; Reitzel & Szatmari, 2003) compared to the general population prevalence rate of MLD (Barbaresi, Katusic, Colligan, Weaver, & Jacobsen, 2005). Moreover, some studies suggested relatively low mathematics scores compared to general functioning. Chiang and Lin (2007) reported in their review, covering an age range of 3-51 years, a relative weakness in mathematics in individuals with ASD. Mayes and Calhoun (2003) reported that 22% of the school-aged (6-15 years) 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 while only 6.1% of them demonstrated a relative weakness. 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. In addition, Soulieres et al. (2010) reported that certain individuals with ASD (9 years of age) may develop superior and specialized abilities in estimation (here operationalized as magnitude comparison).

Finally, some studies argue for *average* or *similar* mathematical abilities in children with ASD when compared to TD peers. Chiang and Lin (2007) reported average math scores in their review when comparing children with ASD to the normed population and Mayes and Calhoun (2003) found no significant differences in IQ and math scores on a standardized achievement in 3- to 7-year-old children with ASD. Iuculano et al. (2014) also reported average abilities on mathematical reasoning compared to TD peers. In addition, studies investigating verbal subitizing reported no differences in accuracy or reaction times between children with and without ASD, aged 10-21 years (Gagnon et al., 2004) and 6-12 years (Jarrold & Russell, 1997).

One explanation of the aforementioned inconsistent findings might be the large behavioral and cognitive heterogeneity observed in the ASD population in general (e.g., Georgiades, Szatmari, & Boyle, 2013), leading to different results depending on the specific sample included; 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) and others on between-group differences (mathematical abilities of children with ASD compared with TD children; e.g., Iuculano et al., 2014).

Objectives and Research Questions

In the current study, a between-group approach was applied to compare the mathematical abilities of children with ASD and TD children. In doing so, we aimed to address 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 (e.g., N. C. Jordan & Levine, 2009). Moreover, results of our previous study on the predictive value of early numerical competencies for first grade mathematics indicated that counting and especially verbal subitizing were important predictors in children with ASD (Author, 2014). As such, it could be informative to compare the performance of children with and without ASD on these foundational precursors. Second, recent studies emphasize the importance of incorporating a multi-componential approach instead of applying one math composite score (J. A. Jordan, Mulhern, & Wylie, 2009; Mazzocco, 2009). Therefore, multiple competencies were investigated in the current study.

The main goal of the current study was to provide an exploratory analysis of the performance of 5- to 6-year old high-functioning children with ASD and TD peers on five early numerical competencies: verbal subitizing, counting, magnitude comparison, estimation, and arithmetic operations. Based on the WCC account, one might expect weaknesses on the processing of 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., prodecural counting and arithmetic operations). However, based on the ED theory, impairments in procedural skills might be assumed. Since no word problems involving mental states were included, we did not assume any influence from the ToM 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 Caucasian preschoolers (45 boys, 15 girls) with a mean age of 5.92 years (*SD* = 0.28) were included in the study. 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. These facilities were contacted by phone and asked to hand out brochures to families who were considered eligible for the current study (based on diagnosis and age). Interested parents were then able to volunteer for the study by contacting the lead investigator. Children with ASD had a formal diagnosis made independently by a qualified multidisciplinary team according to established criteria, such as specified in the DSM-IV-TR (American Psyciatric Association [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 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* .

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*, five children with ASD and two TD children were excluded from the study, resulting in 60 participants. Table 1 provides an overview of the sample characteristics.

< Insert Table 1 about here >

The two groups were matched on age, FSIQ and sex ratio on group level. They were also matched on socio-economic status as measured with the Hollingshead Four Factor Index of social status, which 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 (low SES); 20-29 (lower middle SES); 30-39 (middle SES); 40-54 (upper middle SES); and 55-66 (high SES; Hollingshead, 1975). According to this classification, participants in this study fall, on average, into the upper middle group.

Materials

All materials are described below[1]. Figure 1 provides an example of the test items, Table 2 provides a summarizing table with mean, standard deviation, and range for each outcome for the two groups of preschoolers.

< Insert Figure 1 and Table 2 about here >

Verbal subitizing. 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) was used. One to nine black squares on a white background were displayed on a 17 inch monitor. Participants were instructed to say aloud the number of squares on the screen as quickly and accurately as possible (recording with voice key). 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. The test phase consisted of 72 trials (each numerosity of one to nine was presented eight times) with a central fixation point of 500 ms, a presentation time of 120 ms – in line with the study of Hannula, Räsänen, and Lehtinen (2007) and Fischer et al. (2008), 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 (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 abilities. 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 (Desoete & Grégoire, 2006; Grégoire, 2005; Stock, Desoete, & Roeyers, 2007). Procedural counting (subtest 1; 8 items) was assessed using accuracy in counting row and counting forward to an upper bound and/or from a lower bound. Conceptual counting (subtest 2; 13 items) was assessed by judging the validity of counting procedures.

Children had to judge the counting of linear and nonlinear patterns of objects. Furthermore, they had to construct two numerically equivalent amounts of objects and use counting as a problem-solving strategy in a riddle. 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 et al. (2008) and Inglis, Attridge, Batchelor, and Gilmore (2011), was used. In each trial, two displays of black dots on a white background were presented simultaneously on a 17 inch monitor. Participants were instructed to press the 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 (Dehaene et al., 2005). There were two practice phases and one test phase. 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. In between trials, a blank screen appeared for 500 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 number lines with the left end anchor 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: the visual Arabic format with Arabic numerals (e.g., anchors 0 and 100, target number 2), the auditory verbal format with spoken number words (e.g., anchors zero and hundred, target number two), and the analogue magnitude format, with 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, and were controlled for perceptual variables using the procedure of Dehaene et al. (2005). 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 regarding the accuracy of 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 end B in Siegler & Opfer, 2003). The percentage absolute error (PAE) was calculated per child as a measure of estimation accuracy, following the formula of Siegler and Booth (2004): PAE = |(Estimate – Estimated Quantitiy) / Scale of Estimates| x100. For example, when a child puts a mark at 65 when asked to situate 50 on the number line, 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) 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 respectively the linear and logarithmic model was calculated, resulting in the absolute values of the residuals of the linear and logarithmic fit. Next, a 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, 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 estimations in the middle or positioning all estimations at one anchor).

Arithmetic operations. Arithmetic operations were assessed using a subtest (subtest 5.1; 6 items) of the *TEDI-MATH* (Grégoire et al., 2004) with a series of six visually supported addition and subtraction exercises. 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. Parents received an information letter and signed an informed consent before their participation. The majority of the children were tested in a distraction-free room at the faculty; only a few exceptions of testing at home occurred due to practical reasons. 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* and with the computerized tasks (verbal subitizing and magnitude comparison). Parents were asked to fill out the *SRS* questionnaire. 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 by the lead investigator of the study.

Analyses

First, a Shapiro-Wilk test (for group sizes lower than 50) 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) 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). 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). Since 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 correct responses for the numerosities within the subitizing range). For accuracy, the same analyses were executed, but using the nonparametric variants: a Friedman ANOVA to investigate the effect of on 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-tests for the overall number line task, as well as for the separate presentation formats. Second, on individual level, a Fisher exact test was used to determine whether allocation to the linear/logarithmic/no valid representation categories 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 3 provides an overview of the Spearman correlations between all variables.

< Insert Table 3 about here >

Significantly different correlation patterns seem 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 can be observed in the ASD group. In addition, some significant correlations can be observed within the ASD group between ASD symptom severity (measured with the *SRS*) on the one hand and counting and arithmetic operations on the other hand.

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 by numerosity interaction, $F(5, 25) = 0.64$, $p = .671$, was found, as the reaction times of ASD and TD children mostly overlapped. 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, $F(1, 56) = 0.33$, $p = .570$.

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).

< Insert Figure 2 about here >

Separate Mann-Whitney U tests for the different numerosities showed only a significant 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, $U = 345.00$, $p = .111$. 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).

< Insert Figure 3 about here >

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, $U = 403.00$, $p = .628$.

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, $U = 399.50$, $p = .590$.

Estimation

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

Second, group differences in PAE 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 ($p > .050$).

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 ($R^2_{lin} = .75$, $p = .001$), $t(9) = 3.95$, $p = .003$. 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 ($R^2_{lin} = .74$, $p = .001$), $t(9) = 2.04$, $p = .072$. 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 (respectively .77 and .85), whereas they were low for the ASD group (respectively .43 and .53). 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. The difference in representation for dot patterns is illustrated more in detail in Figure 4.

< Insert Figure 4 about here >

At the individual level, no significant differences were found between the allocation to the 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%) categories between both groups, Fisher exact test, p = .168. 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.

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. 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 a 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 (Author, 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 seem to emerge for TD children and children with ASD for some of the variables. In most of these cases, stronger relationships between the constructs can 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 can be observed between ASD symptom severity (measured with the *SRS*) and counting or arithmetic operations. Together with the aforementioned 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, our sample (5-6 years) was younger than the individuals in the studies of Gagnon et al. (2004) and Jarrold and Russell (1997), which 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 manage 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. Indeed, the use of a serial counting strategy may have been less successful (resulting in lower accuracy scores) in the context of the restricted presentation time of stimuli (i.e., 123 ms) during the enumeration task in our study.

Counting. This study suggests that while children with ASD may be comparable to TD children concerning their procedural counting knowledge, they showed 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, Goldstein, Taylor, &

Siegel, 1994). This differentiation between procedural and conceptual skills in children with ASD can be explained by the central coherence account (Frith & Happe, 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, while 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), this study suggests that these lines 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. However, no significant differences in reaction time or accuracy were found between groups, suggesting that the results 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 also best represented by a logarithmic model. No significant group differences could be found in estimation accuracy. In addition, there were no significant differences between 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 did not differ significantly from each other in either group of children. It should be noted that, while 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, while 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 non-symbolic stimuli on the number line, which was supported by the qualitative observation that children with ASD felt unsure when giving an approximate answer without the possibility to exactly determine the amount of dots by counting. 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.

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 indicates 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 supports can help direct the attention of the child with ASD to the relevant stimuli within the task, thereby helping to organize and process the given information (Hayes et al., 2010).

Strengths and Limitations

The current study provides valuable insights into the important developmental period of preschool age as a transition period in which numbers become increasingly important. Moreover, the current study adds to previous literature by using a multi-componential 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). This enables researchers to obtain a more fine-grained view, because it is possible to compare children with and without ASD on several mathematical components. In addition, the use of a matched control group instead of the normed samples of standardized achievement tests makes a more reliable and direct comparison between children with ASD and TD children possible.

However, given our small sample size and the exploratory nature of the current study, the results 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, certain differences might become significant when using a larger sample size. Moreover, the current study only included high-functioning children with ASD, stemming from a high socio-economic background. Within this context of a highly selective and small sample, the suggested recommendations can also not be extrapolated to the ASD population in general without conducting further research with larger samples including more variation in intellectual functioning and SES. In addition, since autism spectrum conditions 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 to conduct 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-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. However, standardized and frequently used measures were used (e.g., Berteletti et al., 2010; Grégoire et al., 2004; Praet, Titeca, Ceulemans, & Desoete, 2013; Stock et al., 2007), which resulted in similar effects as in previous research ("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).

Implications

Since no robust significant differences could be identified, it can be concluded that the foundation of mathematical development in high-functioning children with ASD may be 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 in this exploratory study. As such, this can be an important message to communicate to parents and teachers if concerns are raised (e.g., before inclusion of a pupil with ASD in a general education classroom). However, the target audience has to be informed that more research on this topic is warranted before a fully informed decision can be made, and that a lot of individual variation exists.

Moreover, the concerns of practitioners of mathematical problems in children with ASD 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 (Author, 2014), these trends might be predictors of concerns for older children. As such, future research should investigate whether these trends become significant when including larger groups of children. Moreover, it will be important to investigate which autism-specific information processing characteristics might influence 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, a weaker central coherence – would be a good candidate to target in such adaptations. Children with ASD, but also TD children, might benefit from explicit instruction when dealing with new material or 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).

We can conclude that despite the observed similarities in early number processing in children with and without ASD, some downward trends indicated a weaker performance of children with ASD on verbal subitizing, conceptual counting, and the estimation of dot patterns. We recommend that these results serve as basis for additional and explanatory research in this field.

Notes

[1] For a more detailed description of materials, please contact the corresponding author.

Conflict of Interest Statement

The authors state no conflict of interest in the current study..

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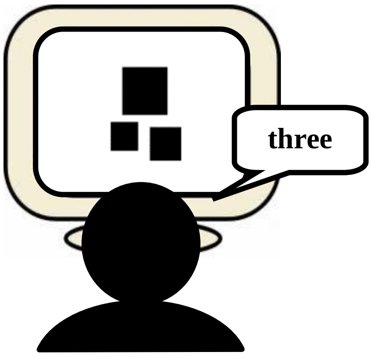


Verbal subitizing

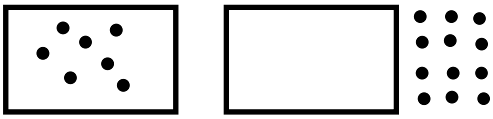
Counting to an upper bound:
Count up to 6.

Counting from a lower bound:
Count from 3.

Counting from a lower to an upper bound:
Count from 5 up to 9.

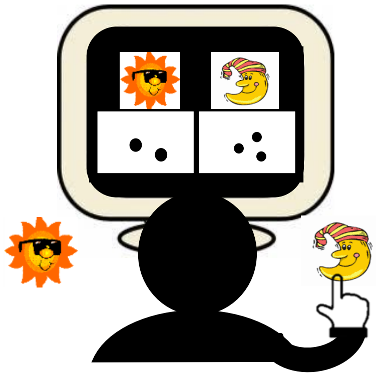
Procedural counting

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?

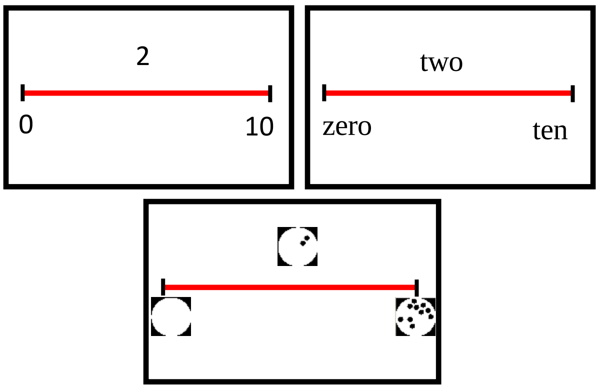


Put as many objects on this board as there are on this one.

Conceptual counting



Magnitude comparison



Estimation

Here you can see two red balloons and three blue balloons.
How many balloons are there in total?

Arithmetic operations

Table 1

Descriptive characteristics of the sample.

	TD n = 30		ASD n = 30		
Sex					
Boys	20		25		$\chi^2(1) = 2.22$, $p = .136$
Girls	10		5		
	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)	$U = 321.50$, $p = .085$
SES[b]	49.18	(7.19)	46.53	(9.67)	$U = 377.50$, $p = .283$
SRS (T-score)[c]	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, non-parametric 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]Socio-economic status, measured with Hollingshead Index; [c]T-score on *Social Responsiveness Scale*.

Table 2

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

		Verbal subitizing		Counting		Magnitude comparison		Estima
		RT[a] (1-3)	Accuracy (1-3)	Procedural	Conceptual	Overall RT[a]	Overall accuracy	Overall PAE[b]
Verbal subitizing								
RT[a] (1-3)	**TD**	**-**						
	ASD	-						
Accuracy (1-3)	**TD**	**-.06**	**-**					
	ASD	-.60****	-					
Counting								
Procedural	**TD**	**-.26**	**.10**	**-**				
	ASD	-.53***	.30	-				
Conceptual	**TD**	**-.47****	**.42****	**.45****	**-**			
	ASD	-.21	.29	.58****	-			
Magnitude comparison								
Overall RT[a]	**TD**	**-.19**	**.36***	**.27**	**.37****	**-**		
	ASD	-.04	.02	-.19	-.05	-		
Overall accuracy	**TD**	**-.20**	**.12**	**.28**	**.08**	**.33**	**-**	
	ASD	-.13	.28	.16	.28	.04	-	
Estimation								
Overall PAE[b]	**TD**	**.28**	**-.16**	**-.26**	**-.33***	**-.10**	**-.25**	**-**
	ASD	.33*	-.44**	-.11	-.17	.24	-.47***	-
Arithmetic operations	**TD**	**-.09**	**.35***	**-.11**	**.37****	**.31***	**.10**	**-.44****
	ASD	-.49***	.40**	.59****	.49***	.03	.19	-.17
FSIQ[c]	**TD**	**-.04**	**.02**	**-.07**	**.03**	**-.12**	**.16**	**-.43****
	ASD	-.37*	.21	.58****	.52***	.05	.31	-.22
SRS[d]	**TD**	**-.18**	**.34***	**.16**	**.11**	**.22**	**.13**	**-.18**
	ASD	.31	-.23	-.44**	-.25	.28	.07	.20

Note. TD = typically developing children; ASD = children with autism spectrum disorder. [a]RT = reaction time; [b]PAE = percentage of absolute error; [c]FSIQ = full scale IQ, measured with *Wechsler Preschool and Primary Scale of Intelligence – Third edition*; [d]SRS = raw score on *Social Responsiveness Scale*
* p < .10, ** p < .05, *** p <.01, ****Bonferroni corrected (p < .001); underlined correlations indicate a significantly stronger correlation than in the other group (Fisher r-to-z transformation, p < .050)

Table 3

Descriptive characteristics of the outcome measures.

	TD					
	n	*M*	(*SD*)	*Range*	*n*	*M*
Verbal subitizing						
Mean RT[a] (1-6)	29	1,289.19	(294.07)	852.41 – 2,069.35	29	1,186.84
Accuracy (% correct, 1-6)	29	67.39	(17.43)	14.58 – 87.50	29	62.42
Counting						
Procedural (% correct)	30	80.83	(20.16)	25.00 – 100.00	30	69.58
Conceptual (% correct)	30	89.49	(10.20)	69.23 – 100.00	30	77.94
Magnitude comparison						
Overall mean RT[a]	29	1,107.77	(240.47)	696.84 – 1,916.46	30	1,099.41
Overall accuracy (% correct)	29	73.47	(9.30)	55.56 – 91.67	30	70.93
Estimation						
Overall PAE[b]	28	18.73	(6.94)	7.70 – 35.65	29	22.22
Arithmetic operations						
Accuracy (% correct)	30	83.89	(19.81)	33.33 – 100.00	30	83.99

Note. TD = typically developing children; ASD = children with autism spectrum disorder. [a]RT = reaction time; [b]PAE = percentage of absolute error