Citation	Brankaer, C., Ghesquière, P., & De Smedt, B. (2013). The development of numerical magnitude processing and its association with working memory in children with mild intellectual disabilities. <i>Research in Developmental Disabilities</i> , 34, 3361-3371. doi: 10.1016/j.ridd.2013.07.001
Archived version	Author manuscript: the content is identical to the content of the published paper, but without the final typesetting by the publisher
Published version	http://www.sciencedirect.com/science/article/pii/S0891422213002941
Journal homepage	http://www.journals.elsevier.com/research-in-developmental-disabilities/
Corresponding author contact	Carmen.Brankaer@ppw.kuleuven.be +32 (0)16 32 61 82
Senior author contact	Bert.DeSmedt@ppw.kuleuven.be +32 (0)16 325705
IR	https://lirias.kuleuven.be

(article begins on next page)

The development of numerical magnitude processing and its association with working
memory in children with mild intellectual disabilities

Carmen Brankaer, Pol Ghesquière, and Bert De Smedt

Parenting and Special Education Research Unit

KU Leuven, Belgium

Correspondence concerning this article should be addressed to Carmen Brankaer, Parenting and Special Education Research Unit, Leopold Vanderkelenstraat 32, box 3765, B-3000 Leuven, Belgium. E-mail: Carmen.Brankaer@ppw.kuleuven.be. Tel. +32 16 32 61 82 or to Bert De Smedt, Parenting and Special Education Research Unit, Leopold Vanderkelenstraat 32, box 3765, B-3000 Leuven, Belgium. E-mail: Bert.DeSmedt@ppw.kuleuven.be. Tel. +32 16 32 57 05. Fax. +32 16 32 59 33

ABSTRACT

The present research examined numerical magnitude processing and its association with working memory in children with mild intellectual disabilities (MID). We investigated the performance of 8-year-old children with MID on a symbolic (Arabic digits) and non-symbolic (dot patterns) magnitude comparison task by means of a chronological-age/ability-level-match design. We also examined whether the predicted problems with numerical magnitude comparison could be explained by working memory by using three working memory tasks. Findings revealed that children with MID performed more poorly than their chronological age-matched peers on both the symbolic and non-symbolic magnitude comparison tasks, suggesting impairments in these children's ability to represent numerical magnitudes. They also performed more poorly on working memory compared to their typically developing age- and ability-matched peers, but when these differences in working memory performance were additionally controlled for, the group differences on the numerical magnitude comparison tasks remained. Both symbolic numerical magnitude processing and central executive functioning predicted addition performance in children with MID.

1. Introduction

In our modern Western societies, numbers and mathematical abilities play a crucial role, for example when getting change in a shop or when reading timetables to catch a bus. Despite the fact that mathematics is interwoven with modern life, 5 to 7% of the population experiences serious difficulties with the development of these mathematical skills (Butterworth, Varma, & Laurillard, 2011). One particular group of individuals that is expected to have mathematical difficulties are children with below-average intellectual abilities (e.g., Hoard, Geary, & Hamson, 1999; Janssen, De Boeck, Viaene, & Vallaey, 1999). Of particular interest for research are the cognitive processes underlying these difficulties, because this knowledge provides a scientifically sound basis for appropriate remedial teaching and mathematics education. In this respect, it has been suggested that the ability to understand and process numerical magnitudes plays a crucial role in the development of mathematical skills (e.g., Butterworth et al., 2011; Gersten, Jordan, & Flojo, 2005). Therefore, a first goal of the present study was to investigate numerical magnitude processing and its development in children with mild intellectual disabilities (MID). Because several studies also pointed to the importance of working memory, a more domain-general factor, for the development of mathematics (e.g., De Smedt et al., 2009a; Friso-van den Bos, van der Ven, Kroesbergen, & van Luit, in press; Swanson & Kim, 2007) and mathematical difficulties (e.g., Swanson & Jerman, 2006), a second goal of the present study was to additionally examine the role of working memory in numerical magnitude processing.

1.1 Numerical magnitude processing

The ability to understand and process numerical magnitude information emerges very early in development, as infants (Xu & Arriaga, 2007) and kindergarteners (Barth, Beckmann, & Spelke, 2008) are able to compare and add sets of non-symbolic objects or dots. Further, it has been suggested that over the course of development, children learn to link these non-symbolic

magnitude representations with number words and Arabic digits (Griffin, 2003). Various studies have highlighted the importance of numerical magnitude representations for successful mathematical development (e.g., Butterworth et al., 2011, for a review). The ability to understand and represent numerical magnitudes seems to be related to and even predictive of mathematics achievement in typically developing children (Bugden & Ansari, 2011; De Smedt, Verschaffel, & Ghesquière, 2009b; Halberda, Mazocco, & Feigenson, 2008; Holloway & Ansari, 2009; Reigosa-Crespo et al., 2012). Furthermore, several studies have shown that children with mathematical difficulties experience problems with numerical magnitude processing (De Smedt & Gilmore, 2011; Landerl, Bevan, & Butterworth, 2004; Mussolin, Mejias, & Noël, 2010).

Two explanations for these problems with numerical magnitude processing have been put forward. These problems might arise from a specific deficit in the innate ability to represent numerical magnitudes, as proposed by the *defective number module hypothesis* (Butterworth, 2005). Another possibility is that these problems originate from impairments in accessing numerical meaning from symbols, as suggested by the *access deficit hypothesis* (Rousselle & Noël, 2007). To disentangle between both hypotheses, one needs to compare children's performance on a symbolic (Arabic digits) and non-symbolic (dot patterns) numerical magnitude comparison task (Sekuler & Mierkiewicz, 1977), in which children have to indicate the numerically larger of two presented quantities. If children with mathematical difficulties perform more poorly than typically developing children on both tasks, this favors the defective number module hypothesis. If, by contrast, children with mathematical difficulties perform more poorly than typically developing children on the symbolic, but not on the non-symbolic magnitude comparison task, this supports the access deficit hypothesis. Although most of the existing body of data indicates that children with mathematical difficulties show deficits in their ability to compare Arabic digits, data on non-symbolic

magnitude comparison tasks have been inconclusive so far (see De Smedt, Noël, Gilmore, & Ansari, in press; Noël & Rousselle, 2011 for an overview).

It is important to point out that this existing body of data only deals with children with mathematical disabilities and that these findings may therefore not be readily generalized to children with MID. Only but a few attempts have been made to examine numerical magnitude comparison in children with a below-average intelligence or MID. Hoard et al. (1999) revealed that these children ($M_{IQ} = 78$) were less accurate in comparing Arabic digits than their typically developing peers. However, only a symbolic magnitude comparison task was included in this study, which makes it impossible to determine whether the children also had problems with non-symbolic magnitude comparison. More recently, Brankaer, Ghesquière and De Smedt (2011) investigated numerical magnitude processing in 10-11-year-old children with MID ($M_{IQ} = 62$) more systematically by comparing the performance of these children on both a symbolic and non-symbolic magnitude comparison task with the performance of two control groups of typically developing children: One control group matched on chronological age to the children with MID and one control group matched on arithmetic achievement level to the children with MID. Findings of this study demonstrated that children with MID performed more poorly than their chronological age-matched peers on both the symbolic and non-symbolic magnitude comparison tasks, although their difficulties on the symbolic task were more pronounced.

It should be noted that the children in the study of Brankaer et al. (2011) were relatively old and already received some years of (adapted) mathematics education. As Soltész, Szűcs and Szűcs (2010) mentioned, the development of numerical magnitude representation is supported and largely influenced by formal education and numerical enculturation. Therefore, it might be interesting to examine whether the results of Brankaer et al. (2011) can be replicated in younger children with MID, which was the aim of the present study.

1.2 Working memory

The present study also focused on working memory as a determinant of children with MID's mathematical difficulties, because various studies in typically developing children and children with mathematical difficulties have shown that this domain-general factor also plays an important role in, and even predicts, mathematics performance (Bull, Espy, & Wiebe, 2008; De Smedt et al., 2009a; Passolunghi & Siegel, 2004; Passolunghi, Vercelloni, & Schadee, 2007; Swanson & Kim, 2007). More specifically, because recent data pointed to an association between working memory and numerical magnitude processing (Gullick, Sprute, & Temple, 2011; Passolunghi & Lanfranchi, 2012) and several studies indicated working memory impairments in children with MID (e.g., Henry & MacLean, 2002; Schuchardt, Gebhardt, & Mäehler, 2010; Van der Molen, Van Luit, Jongmans, & Van der Molen, 2009), we aimed to examine whether the predicted difficulties with numerical magnitude comparison in children with MID could be explained by working memory.

The concept of working memory refers to a system that temporarily stores and manipulates information (Baddeley, 2003). A widely used model of working memory is the multi-component model of Baddeley (1986, 2003), which has three main components. A first component is the central executive, a system that controls and regulates complex cognitive processes. This component is typically measured with complex span tasks, in which participants have to manipulate the information before they can replicate it. The other two components are called slave systems, and are only used for passive information storage: the phonological loop stores verbal and auditory information while the visual-spatial sketchpad is responsible for the storage of visual and spatial information. These two components are usually measured with simple span tasks, in which children have to repeat a series of phonological or visual-spatial items without manipulation. Both slave systems are in direct contact with the central executive. All three working memory components of Baddeley's

model are assumed to play a role in mathematics performance, although task- and age-related differences with regard to the contribution of the different components have been observed (Bull et al., 2008; De Smedt et al., 2009a; DeStefano & LeFevre, 2004; Henry & MacLean, 2003).

Numerous studies have examined working memory in children with intellectual disabilities by using a chronological-age/mental-age-match design (e.g., Henry & MacLean, 2002; Schuchardt et al., 2010; Van der Molen et al., 2009). There is converging evidence that children with MID experience problems with all components of working memory compared to their chronological age-matched peers (Schuchardt et al., 2010; Van der Molen et al., 2009). The results of comparisons between children with MID and mental age-matched children, however, have been less clear, partly because various studies involved different populations, i.e. children differing in age and in degree of intellectual disability, and used different tasks to measure working memory (Henry & MacLean, 2002; Schuchardt et al., 2010; Van der Molen et al., 2009). Nevertheless, the findings of these studies suggest that children with MID have problems with several components of working memory even when compared to their mental-age matched peers.

1.3 The present study

The aim of the present study was to examine numerical magnitude processing and its association with working memory in children with MID. Firstly, because the development of numerical magnitude representation is largely influenced by formal education (Soltész et al., 2010), we wanted to investigate whether the results of Brankaer et al. (2011) could be replicated in younger children with MID. It might be that difficulties in non-symbolic magnitude processing were already compensated in older children with MID (see De Smedt & Gilmore, 2011 for a similar rationale in children with an average intelligence and mathematical difficulties). If this hypothesis is true, we expect larger differences in

non-symbolic number representations in younger children with MID. Alternatively, Noël and Rousselle (2011) hypothesized that difficulties in non-symbolic magnitude processing result from a basic dysfunction in the building process of an exact representation of symbolic numbers. This developmental perspective was, however, based on developmental data from children with dyscalculia and can therefore not be easily generalized to children with MID. Nevertheless, if the hypothesis of Noël and Rousselle (2011) is true, and if children with MID would follow the same developmental trajectory as children with dyscalculia, we particularly expect differences on the symbolic magnitude comparison task and smaller differences on the non-symbolic task in younger children with MID. To investigate these two possibilities, we systematically assessed symbolic and non-symbolic magnitude comparison in 8-year-old children with MID. Additionally, in line with Brankaer et al. (2011), we tried to examine whether the development of magnitude representation in children with MID simply lags behind that of typically developing individuals (*delay hypothesis*) or whether the development of children with MID is marked by deficits in specific cognitive processes, which makes the general principles of development not applicable (*deficit hypothesis*) (Bennett-Gates & Zigler, 1998). This was done by comparing the performance of children with MID with the performance of two control groups of typically developing children: one group matched on chronological age to the children with MID and one group matched on arithmetic achievement level to the children with MID. If the performance of children with MID differs from the performance of chronological age matched children but not from the performance of arithmetic achievement matched children, then their development is marked by a delay. If, by contrast, their performance differs from the performance of both control groups, then their development is marked by a deficit. Based on the results of Brankaer et al. (2011), who suggested that the development of numerical magnitude representation in children with MID is marked by a delay, we hypothesized that the performance of our participants with MID

would differ from the performance of their chronological age matched peers, but not from younger children with the same arithmetic achievement level. Because children's reaction time on the numerical magnitude comparison tasks might be influenced by their general processing speed, we also assessed a motor reaction time task to control for this variable in our analyses.

Secondly, against the background of the found associations between working memory and numerical magnitude processing (Gullick et al., 2011; Passolunghi & Lanfranchi, 2012) and the working memory impairments in children with MID (e.g., Henry & MacLean, 2002; Schuchardt et al., 2010, Van der Molen et al., 2009), we also aimed to unravel whether the predicted problems with numerical magnitude comparison in children with MID could be explained by working memory. Additionally, we tried to examine the association between working memory, numerical magnitude processing and arithmetical ability in more detail, an issue that has not been examined so far in children with MID.

2. Method

2.1 Participants

Participants with MID were selected from four special education schools that are specifically organized for children with MID. Control children were recruited from six mainstream primary schools. Parental consent was obtained for 294 children, who all completed a standardized arithmetic test (de Vos, 1992) to determine their arithmetic achievement level.

Because all children with MID needed a clinical diagnosis of MID and an attest that reports on their intelligence to get enrolled in special education schools for MID, intelligence scores for children with MID were retrieved from their school records. The following three standardized intelligence tests were administered as measures of intellectual ability: (1) the Dutch version of the Wechsler Preschool and Primary Scale of Intelligence - Revised

(WPPSI-R^{NL}; Vander Steene & Bos, 1997), (2) the Dutch version of the Wechsler Intelligence Scale for Children - Third Edition (WISC-III^{NL}; Kort et al., 2005), or (3) Snijders-Oomen Nonverbal Intelligence Test Revised (SON-R 2.5-7; Tellegen et al., 1998). All intelligence tests were administered by specifically trained school psychologists. Against the background of the DSM-IV-TR criteria for defining mild intellectual disabilities (APA, 2000), only children with an IQ between 55 and 75 were included in the group of children with MID. Moreover, we excluded children with known genetic syndromes that are associated with mathematical difficulties (i.e., Williams-Beuren syndrome, Velo-cardio-facial syndrome, Turner syndrome, Down syndrome and Fragile X syndrome).

All control children completed the Raven's Standard Progressive Matrices (Raven, Court, & Raven, 1992) as a measure of intellectual ability to verify if they had average intellectual ability (i.e. between 85 – 115). None of them had a developmental disorder and none of them had repeated grade. Two control groups were selected: one group matched on chronological age to the children with MID (CA-group) and one group matched on arithmetic achievement level to the children with MID (AL-group).

The final sample consisted of 31 children with MID, 31 CA-matched controls and 31 AL-matched controls. Table 1 shows the descriptive statistics of these three groups. The groups did not differ in the number of boys and girls, $\chi^2(2, N = 93) = 1.64, p = .44$. As expected, the groups differed in chronological age, $F(2,90) = 116.12, p < .01, \eta_p^2 = .72$: children from the AL-group were significantly younger than children with MID ($p < .01, d = -2.87$) and children from the CA-group ($p < .01, d = -5.56$), while these latter two groups did not differ ($p = .93$). Further, groups differed in intellectual ability ($F(2,90) = 672.63, p < .01, \eta_p^2 = .89$), as children with MID had a significantly lower intellectual ability than children from the CA-matched ($p < .01, d = -6.72$) and AL-matched ($p < .01, d = -5.99$) control groups, who did not differ from each other ($p = .46$). Finally, groups differed in

arithmetical ability, $F(2,90) = 156.75$, $p < .01$, $\eta_p^2 = .78$: children from the CA-matched control group could solve significantly more addition problems than children with MID ($p < .01$, $d = 3.78$) and children from the AL-group ($p < .01$, $d = 3.63$), who in turn did not differ ($p = .18$). These findings indicate that the three groups were successfully matched.

2.2 Procedure

All participants were tested at their own school during regular school hours and they all completed the group-administered arithmetic achievement test. Additionally, control children also completed the measure of intellectual ability, which was group-based. After that, the computerized tasks and working memory tasks were individually administered in a quiet room.

2.3 Measures

2.3.1 Group administered tasks

2.3.1.1 Arithmetical ability

All children completed the Tempo Test Arithmetic (de Vos, 1992), a standardized paper-and-pencil achievement test for arithmetic, as a measure of arithmetical ability. In this test, children were asked to solve basic arithmetic problems as accurately and quickly as possible (e.g., $7 + 2 =$). For each operation, 40 problems of increasing difficulty were presented and children were required to solve as many problems as possible within a one-minute period. In this study, only the addition problems were presented, as the children with MID did not yet receive enough instruction in other operations. The score on this test was the number of correctly solved problems within the time limit of one minute.

2.3.1.2 Intellectual ability

Raven's Standard Progressive Matrices (Raven et al., 1992) was used to verify that all control children had average intellectual ability. For each child in the CA- and AL-group, a standardized score ($M = 100$; $SD = 15$) was calculated.

2.3.2 Computerized tasks

The computerized tasks were presented using the E-prime 2.0 software (Schneider, Eschmann, & Zuccolotto, 2002) and were all administered using a 15 inch laptop. Children were instructed to perform both accurately and quickly. Stimuli occurred in white on a black background in Arial font (size 72). Each trial started with a 250 ms fixation cross in the centre of the computer screen. After 1000 ms the stimuli appeared and remained visible until response, except for the non-symbolic magnitude comparison task where the stimuli disappeared after 840 ms, in order to avoid counting. Each trial was initiated by the experimenter by means of a control key. In these computer tasks, participants had to respond by pressing a key on a computer keyboard that was put in front of the laptop and was connected to it. The left response key, labeled with a blue sticker, was 'd'; the right response key, labeled with a yellow sticker, was 'k'. Each task was preceded by three practice trials to familiarize the child with the key assignments. Answers and reaction times were recorded by the laptop.

2.3.2.1 Symbolic magnitude comparison

A classic numerical magnitude comparison task (Sekuler & Mierkiewicz, 1977) was administered. In this task, children had to indicate the numerically larger of two simultaneously presented Arabic digits, one displayed on the left and one displayed on the right side of the computer screen. Stimuli involved all combinations of the digits 1 to 9, yielding 72 trials. Children had to answer by pressing the response key on the side of the larger digit. The position of the largest digit was counterbalanced.

2.3.2.2 Non-symbolic magnitude comparison

Children had to indicate the larger of two simultaneously presented dot arrays, one displayed on the left and one displayed on the right side of the computer screen. Stimuli comprised the same numerosities as in the symbolic magnitude comparison task, yielding 72 trials. The

stimuli were generated by means of the MATLAB script provided by Piazza, Izard, Pinel, Le Bihan and Dehaene (2004) and were controlled for non-numerical parameters, i.e. individual dot size, total occupied area, and density. This was done to reduce the likelihood that children would rely on these non-numerical cues or perceptual features to make a correct decision. Similar to the symbolic magnitude comparison task, children had to select the larger numerosity by pressing the response key on the side of the larger numerosity. The position of the largest numerosity was counterbalanced.

2.3.2.3 Control task: Motor reaction time

This task was included as a control for children's response speed on the keyboard. Two figures appeared on the screen. One of them was coloured white and the child had to press as soon as possible on the side of this white figure. Twenty experimental trials were presented.

2.3.3 Working memory

2.3.3.1 Phonological loop

In the *Digit Span Forward task* a series of digits between 1 and 9 was presented acoustically. These series were recorded to standardize the assessment. Children had to repeat the digits immediately in the presented order. There were three trials for each span length (from two to nine digits). The first two trials were taken from the Wechsler Intelligence Scale for Children - 3rd Edition (WISC-III) (Wechsler, 1992) and the third trial was taken from the Working Memory Test Battery for Children (WMTB-C) (Pickering & Gathercole, 2001). When the child failed three successive trials of the same length, testing on this task was terminated.

2.3.3.2 Visual-spatial sketchpad

In the *Corsi Block task*, the experimenter tapped out a sequence on a board with nine blocks. Children had to repeat this sequence in the same order. The task started with a sequence of two blocks, and gradually became more difficult (from two to nine blocks, with three trials for

each span length). When the child failed two trials of the same length, testing on this test was terminated.

2.3.3.3 Central executive

The *Digit Span Backward task* was similar to the Digit Span Forward task, both for construction and administration, except that children had to repeat the sequence of auditory presented digits between 1 and 9 in the reverse order. Testing on this task was terminated when the child failed two trials of the same length.

2.4 Statistical analyses

Group differences were evaluated by means of ANOVA. All post-hoc *t*-tests were Bonferroni corrected. Partial eta-squared and Cohen's *d* were calculated as measures of effect size.

3. Results

3.1 Control task

Before we turn to the results on the numerical magnitude comparison tasks, performance on the motor reaction task was examined. Accuracy on this task was very high and at ceiling (MID: 97%, AL: 96% and CA: 98%). With respect to children's response speed, group differences were found by means of a one-way ANOVA, $F(2,90) = 16.11$, $p < .01$, $\eta_p^2 = .26$: CA-matched children ($M = 445.56$ ms, $SD = 51.91$) were significantly faster than children with MID ($M = 625.31$ ms, $SD = 189.47$; $p < .01$, $d = -1.32$) and AL-matched children ($M = 591.02$ ms, $SD = 118.28$; $p < .01$, $d = -1.61$), whereas the latter two groups did not differ from each other, $p = .93$. These differences were considered in subsequent analyses.

3.2 Numerical magnitude comparison

Accuracy on the numerical magnitude comparison tasks is shown in Figure 1. To evaluate group differences, a repeated measures ANOVA with task (symbolic vs. non-symbolic) as within-subject factor and group as between-subject factor was used. There was a main effect of group, $F(2,90) = 14.06$, $p < .01$, $\eta_p^2 = .24$, indicating that children with MID performed less

accurately than AL-matched children ($p = .04$, $d = -0.49$) and CA-matched children ($p < .01$, $d = -1.12$). Additionally, AL-matched children performed less accurately than CA-matched children ($p = .02$, $d = -0.88$). There was no main effect of task, $F(1,90) = 0.92$, $p = .34$, $\eta_p^2 = .01$, and no significant Group $\times$ Task interaction, $F(2,90) = 1.29$, $p = .28$, $\eta_p^2 = .03$.

Reaction times were based on correct responses only. To account for group differences in accuracy, adjusted reaction times were calculated by dividing children's reaction times by their accuracy scores (see Figure 2). Again, a repeated measures ANOVA with task (symbolic vs. non-symbolic) as within-subject factor and group as between-subject factor was used to evaluate group differences. A main effect of group was found, $F(2,90) = 43.56$, $p < .01$, $\eta_p^2 = .49$, indicating that CA-matched children were significantly faster than AL-matched children ($p < .01$, $d = -2.03$) and children with MID ($p < .01$, $d = -1.50$), while the latter two groups did not differ from each other ($p = .13$). There was also a main effect of task, $F(1,90) = 19.86$, $p < .01$, $\eta_p^2 = .18$: Children were faster on the non-symbolic magnitude comparison task than on the symbolic task. Further, a significant Group $\times$ Task interaction was found, $F(2,90) = 3.80$, $p = .03$, $\eta_p^2 = .08$, revealing that the difference between children with MID and CA-matched children was more prominent on the symbolic ($p < .01$, $d = 2.28$) than on the non-symbolic comparison task ($p < .01$, $d = 1.05$). To evaluate whether these findings could be explained by individual differences in motor reaction time, we repeated the analysis with this variable as a covariate. After controlling for motor reaction time, the main effect of group remained, $F(2,89) = 20.58$, $p < .01$, $\eta_p^2 = .32$, demonstrating that CA-matched children remained significantly faster than AL-matched children and children with MID ($ps < .01$, $ds < -0.90$), while the latter two groups did not differ ($p = .25$).

3.3 Working memory

Children's performance on the working memory tasks is shown in Figure 3. Group differences were evaluated by means of one-way ANOVAs and post-hoc t -tests that were

Bonferroni corrected. Groups differed on the Digit Span Forward task, $F(2,90) = 26.63$, $p < .01$, $\eta_p^2 = .37$: Children from the CA-group performed significantly better than children from the AL-group ($p < .01$, $d = 0.83$) and children with MID ($p < .01$, $d = 2.00$). Moreover, AL-matched children performed better than children with MID ($p < .01$, $d = 0.99$). Similar group differences were found for the Corsi Block task ($F(2,90) = 39.01$, $p < .01$, $\eta_p^2 = .46$) and the Digit Span Backward task ($F(2,90) = 39.99$, $p < .01$, $\eta_p^2 = .47$), demonstrating that CA-matched children performed better than AL-matched children (Corsi Block: $p < .01$, $d = 1.25$; Digit Span Backward: $p < .01$, $d = 1.36$) and children with MID (Corsi Block: $p < .01$, $d = 2.45$; Digit Span Backward: $p < .01$, $d = 2.13$). Additionally, children from the AL-group performed better than children with MID on both the Corsi Block ($p < .01$, $d = 0.96$) and Digit Span Backward ($p < .01$, $d = 0.98$) tasks.

3.4 Numerical magnitude comparison and working memory

To examine whether the observed group differences in numerical magnitude comparison could be explained by group differences in working memory, we repeated the abovementioned analyses for the numerical magnitude comparison tasks with working memory as covariate.

With regard to accuracy, the main effect of group remained when controlling for children's performance on the Digit Span Forward ($F(2,89) = 10.66$, $p < .01$, $\eta_p^2 = .19$), the Corsi Block ($F(2,89) = 7.02$, $p < .01$, $\eta_p^2 = .14$) and the Digit Span Backward task ($F(2,89) = 8.06$, $p < .01$, $\eta_p^2 = .15$). Children with MID performed less accurately than AL-matched children ($ps \leq .05$, $ds < -0.63$), although only a marginally significant trend towards a difference between both groups was observed when the Corsi Block task was included as a covariate ($p = .09$, $d = -0.56$). Further, both children with MID and AL-matched children performed less accurately than CA-matched children ($ps \leq .05$, $ds < -0.65$).

Similar results were obtained for reaction times. The main effect of group remained when controlling for children's performance on the working memory tasks (Digit Span Forward: $F(2,89) = 22.11$, $p < .01$, $\eta_p^2 = .33$; Corsi Block: $F(2,89) = 19.08$, $p < .01$, $\eta_p^2 = .30$; Digit Span Backward: $F(2,89) = 17.20$, $p < .01$, $\eta_p^2 = .28$), indicating that CA-matched children were significantly faster than AL-matched children ($ps < .01$, $ds < -1.38$) and children with MID ($ps < .01$, $ds < -1.62$), while the latter two groups did not differ from each other ($ps > .44$, $ds > -0.36$).

3.5 Additional analyses

Pearson correlation coefficients were calculated to examine the association between working memory, numerical magnitude representations and mathematics in children with MID more into detail. As shown in Table 2, children's performance on the Tempo Test Arithmetic was significantly correlated with their score on the Digit Span Backward task, indicating that children with better central executive resources solved more addition problems within one minute. We also found a significant correlation between children's reaction time on the symbolic magnitude comparison task and their performance on the Tempo Test Arithmetic, indicating that the faster children with MID were when comparing Arabic digits, the higher their score on the arithmetic achievement test. No associations between mathematical ability and non-symbolic magnitude comparison or other working memory measures were found.

We further ran a regression analysis to assess the amount of unique variance in arithmetical ability that could be explained by both working memory and numerical magnitude processing. The tasks that significantly correlated with the Tempo Test Arithmetic were simultaneously entered in the model (see Table 3). Our findings revealed that both performance on the Digit Span Backward task and reaction time on the symbolic magnitude comparison task accounted for a significant proportion of variance in arithmetical ability in children with MID.

4. Discussion

Children with MID are known to have difficulties with the development of mathematical abilities (Brankaer et al., 2011; Hoard et al., 1999; Janssen et al., 1999). Understanding the cognitive processes underlying these difficulties is crucial to design appropriate remedial interventions. The present study examined the role of numerical magnitude processing in relation to the mathematical difficulties that children with MID experience. More specifically, we systematically investigated symbolic and non-symbolic magnitude comparison in 8-year-old children with MID. Our data indicate that these children are impaired in their ability to represent numerical magnitudes. To determine whether these difficulties with numerical magnitude comparison could be explained by working memory, we further examined the association between working memory, numerical magnitude processing and arithmetical ability more into detail. These data indicate that the working memory problems in children with MID do not account for the observed group differences in numerical magnitude comparison. Importantly, we also found that both symbolic numerical magnitude processing and central executive functioning were unique predictors of individual differences in addition performance in children with MID.

Consistent with Hoard et al. (1999) and Brankaer et al. (2011), results showed that 8-year-old children with MID have particular problems with numerical magnitude representations compared to their typically developing chronological-age matched peers. These data are also in line with studies that found numerical magnitude processing impairments in children with an average intelligence and mathematical difficulties or dyscalculia (De Smedt & Gilmore, 2011; Landerl et al., 2004; Mussolin et al., 2010), although caution is needed when generalizing these findings in dyscalculia to children with MID. Furthermore, we found that children with MID performed more poorly on both the symbolic and non-symbolic magnitude comparison task, consistent with the defective number module hypothesis. The reaction time

data, however, revealed that the group differences were most prominent on the symbolic magnitude comparison task. These findings are similar to those of Brankaer et al. (2011) and suggest that children with MID also have particular problems in accessing numerical meaning from symbols.

The present study used a chronological-age/ability-level-match design to further unravel whether the development of magnitude representation in children with MID was marked by a delay or a deficit. Results were not easy to interpret because children with MID performed less accurately but equally fast as children from the AL-group on the numerical magnitude comparison tasks. However, because Brankaer et al. (2011) found that older children with MID performed as accurately as their AL-matched peers, it seems that the general development of magnitude representation in children with MID is delayed, but not fundamentally different from that of typically developing individuals.

Can the problems with numerical magnitude representation in children with MID be explained by their poor working memory abilities? To answer this question, we additionally investigated working memory skills in our sample. Children with MID performed more poorly than children from the CA- and AL-group on all three working memory tasks, suggesting deficits in the central executive, the visual-spatial sketchpad and the phonological loop. These results are partially in line with Van der Molen et al. (2009), who found that children with MID performed more poorly than their mental-age-matched peers on the Digit Span Backward and Corsi Block task. Regarding the Digit Span Forward task, however, Van der Molen et al. (2009) found no significant differences between the performance of children with MID and their mental-age-matched peers. Further, Schuchardt et al. (2010) found no group differences on the Digit Span Backward and Corsi Block task when comparing the performance of children with MID and children from the mental-age matched group. It is crucial to note that in the current study, control children were matched on arithmetic

achievement level rather than mental age, which is different from the working memory studies in MID reported above. This was done because children's numerical processing skills are supported and largely influenced by formal mathematics education (Soltész et al., 2010). Therefore, a matching based on arithmetic achievement level seemed most appropriate when focusing on numerical magnitude processing. It is important to emphasize that this matching procedure limits the comparability of the current findings with previous working memory studies in children with MID. Future studies should therefore replicate the current research by using a control group that is matched on mental age rather than mathematics achievement level.

The working memory impairments in children with MID could, however, not explain the observed difficulties with numerical magnitude processing, as the group differences on the numerical magnitude comparison tasks remained when working memory was additionally controlled for. Moreover, the regression analysis indicates that both children's symbolic magnitude comparison skills and central executive resources are uniquely related to their performance on an arithmetic achievement test. These findings are, on the one hand, in accordance with studies that showed that working memory is associated with mathematics achievement (Bull et al., 2008; De Smedt et al., 2009a; Passolunghi & Siegel, 2004; Passolunghi et al., 2007; Swanson & Kim, 2007) and, on the other hand, consistent with studies that highlighted the importance of symbolic numerical magnitude processing for the development of mathematical abilities (De Smedt et al., 2009b; De Smedt & Gilmore, 2011; Holloway & Ansari, 2009; Landerl et al., 2004; Rousselle & Noël, 2007). Additionally, the present findings support previous studies in typically developing children that found that both working memory and numerical magnitude representations are uniquely related to the development of mathematics (Geary, Hoard, Nugent, & Bailey, 2012; Passolunghi & Lanfranchi, 2012) and indicate that these findings can be generalized to children with MID.

An important limitation of the present study is that it was cross-sectional in nature, i.e. we tried to replicate the findings of Brankaer et al. (2011) in 8-year-old children with MID to gain insight into the developmental process of numerical magnitude representation in children with MID. A longitudinal design, in which one cohort is followed over time, would be more appropriate to obtain information about children's individual development. Moreover, a longitudinal design would allow us to determine whether the numerical processing skills of children with MID can actually predict their later mathematical abilities (see De Smedt et al., 2009b for a similar rationale).

The current findings have important implications for the screening and (remedial) mathematics education of children with MID. Firstly, our data indicate that symbolic numerical magnitude processing and central executive functioning are related to mathematics achievement within the group of children with MID, suggesting that children with lower magnitude processing skills or lower working memory capacities are most at risk for mathematical difficulties. Therefore, it might be useful to develop screening tools to identify these at-risk children at an early age. An example of a potential screening instrument that focuses on children's numerical magnitude representations is '*The Number Sets Test*' (Geary, Bailey, & Hoard, 2009), although the utility of this instrument for predicting mathematics achievement in children with MID still needs to be evaluated.

Secondly, because children with MID already have problems with numerical magnitude processing at the start of formal mathematics education, interventions should foster the development of numerical magnitude representations from an early age. Moreover, because these children seem to have particular problems with symbolic magnitude representations and a relation between their symbolic processing skills and mathematics achievement was found, interventions should not only focus on the development of magnitude representations per se, but they should also provide plenty of opportunities where children with MID learn to connect

symbols and the quantities they represent. These interventions could be presented in game-like formats, such as linear numerical board games (e.g., Ramani and Siegler, 2011). Board games could enhance children's understanding of numerical symbols because they provide multiple cues to the connection between symbols and their quantities. For instance, the larger the numerical symbol in a square of the board game, the larger the number of movements of the token a child has made and the larger the number of number words a child has heard and said (Siegler, 2009). There also exist computerized intervention programs that focus on the association of numerical symbols with their numerical meaning (Kucian et al., 2011; Wilson, Revkin, Cohen, Cohen, & Dehaene, 2006). For future research, it might be interesting to evaluate the effect of these games in children with MID.

Against the background of the working memory problems in children with MID, it might be worthwhile to explore training programs that target working memory (e.g., Melby-Lervåg & Hulme, 2013, for a review). Most of these training programs focused on typically developing children and children with ADHD or learning disabilities, although Van der Molen, Van Luit, Van der Molen, Klugkist and Jongmans (2010) developed a computerized working memory training specifically for adolescents with mild to borderline intellectual disabilities. While several training programs seemed to have short-term effects on children's working memory capacity, the generalization of working memory training to other skills, such as arithmetic, remains to be rather limited (Melby-Lervåg & Hulme, 2013), although Van der Molen et al. (2010) showed that a working memory training in adolescents led to higher scores in arithmetic at the follow-up test after the intervention compared to the control condition. Future research should therefore test whether such generalization effects also occur in primary school children with MID.

5. Acknowledgements

We would like to thank all participating children, parents and teachers. This study was supported by the Marguerite-Marie Delacroix Support Fund.

6. References

- American Psychiatric Association. (2000). *Diagnostic and statistical manual of mental disorders*, (4th ed., text revision). Washington, DC: American Psychiatric Association.
- Baddeley, A. D. (1986). *Working memory*. New York: Clarendon.
- Baddeley, A. (2003). Working memory: Looking back and looking forward. *Nature Reviews Neuroscience*, 4, 829-839.
- Barth, H., Beckmann, L., & Spelke, E. S. (2008). Nonsymbolic, approximate arithmetic in children: Abstract addition prior to instruction. *Developmental Psychology*, 44, 1466-1477.
- Bennett-Gates, D., & Zigler, E. (1998). Resolving the developmental-difference debate: An evaluation of the triarchic and systems theory models. In Burack, J.A., Hodapp, R.M, & Zigler, E. (Eds.), *Handbook of Mental Retardation and Development*. (pp. 115-131). Cambridge, UK: Cambridge University Press.
- Brankaer, C., Ghesquière, P., & De Smedt, B. (2011). Numerical magnitude processing in children with mild intellectual disabilities. *Research in Developmental Disabilities*, 32, 2853-2859.
- Bugden, S., & Ansari, D. (2011). Individual differences in children's mathematical competence are related to the intentional but not automatic processing of Arabic numerals. *Cognition*, 118, 32-44.
- Bull, R., Espy, K. A., & Wiebe, S. A. (2008). Short-term memory, working memory and executive functioning in preschoolers: longitudinal predictors of mathematical achievement at age 7 years. *Developmental Neuropsychology*, 33, 205-228.
- Butterworth, B. (2005). Developmental dyscalculia. In J. I. D. Campbell (Ed.), *Handbook of Mathematical Cognition* (pp. 455-467). Hove: Psychology Press.
- Butterworth, B., Varma, S., & Laurillard, D. (2011). Dyscalculia: From brain to education. *Science*, 332, 1049-1053.

De Smedt, B., & Gilmore, C. K. (2011). Defective number module or impaired access? Numerical magnitude processing in first graders with mathematical difficulties. *Journal of Experimental Child Psychology*, 108, 278-292.

De Smedt, B., Janssen, R., Bouwens, K., Verschaffel, L., Boets, B., & Ghesquière, P. (2009a). Working memory and individual differences in mathematics achievement: a longitudinal study from first grade to second grade. *Journal of Experimental Child Psychology*, 103, 186-201.

De Smedt, B., Noël, M. P., Gilmore, C., & Ansari, D. (in press). The relationship between symbolic and non-symbolic numerical magnitude processing and the typical and atypical development of mathematics: evidence from brain and behavior. *Trends in Neuroscience and Education*.

De Smedt, B., Verschaffel, L., & Ghesquière, P. (2009b). The predictive value of numerical magnitude comparison for individual differences in mathematics achievement. *Journal of Experimental Child Psychology*, 103, 469-479.

DeStefano, D., & LeFevre, J.-A. (2004). The role of working memory in mental arithmetic. *European Journal of Cognitive Psychology*, 16, 353-386.

De Vos, T. (1992). Tempo-Test-Rekenen. Test voor het vaststellen van het rekenvaardigheidsniveau der elementaire bewerkingen (automatisering) voor het basis- en voortgezet onderwijs. Handleiding. Nijmegen: Berkhout.

Friso-van den Bos, I., van der Ven, S. H. G., Kroesbergen, E. H., & van Luit, J. E. H. (in press). Working memory and mathematics in primary school children: A meta-analysis. *Educational Research Review*.

Geary, D. C., Bailey, D. H., & Hoard, M. K. (2009). Predicting mathematical achievement and mathematical learning disability with a simple screening tool: The Number Sets Test. *Journal of Psychoeducational Assessment*, 27, 265-279.

- Geary, D. C., Hoard, M. K., Nugent, L., & Bailey, D. H. (2012). Mathematical cognition deficits in children with learning disabilities and persistent low achievement: a five-year prospective study. *Journal of Educational Psychology, 104*, 206-223.
- Gersten, R., Jordan, N. C., & Flojo, J. R. (2005). Early identification and interventions for students with mathematics difficulties. *Journal of Learning Disabilities, 38*, 293-304.
- Griffin, S. (2003). The development of math competence in the preschool and early school years: cognitive foundations and instructional strategies. In J. M. Royer (Ed.), *Mathematical Cognition* (1-32). Connecticut: Information Age Publishing.
- Gullick, M. M., Sprute, L. A., & Temple, E. (2011). Individual differences in working memory, nonverbal IQ, and mathematics achievement and brain mechanisms associated with symbolic and nonsymbolic number processing. *Learning and Individual Differences, 21*, 644-654.
- Halberda, J., Mazocco, M. M. M., & Feigenson, L. (2008). Individual differences in non-verbal number acuity correlate with maths achievement. *Nature, 455*, 665-668.
- Henry, L., & MacLean, M. (2002). Working memory performance in children with and without intellectual disabilities. *American journal of Mental Retardation, 107*, 421-432.
- Henry, L., & MacLean, M. (2003). Relationships between working memory, expressive vocabulary and arithmetical reasoning in children with and without intellectual disabilities. *Educational and Child Psychology, 20*, 51-63.
- Hoard, M. K., Geary, D. C., & Hamson, C. O. (1999). Numerical and arithmetical cognition: performance of low- and average-IQ children. *Mathematical Cognition, 5*, 65-94.
- Holloway, I. D., & Ansari, D. (2009). Mapping numerical magnitudes onto symbols: The numerical distance effect and individual differences in children's mathematics achievement. *Journal of Experimental Child Psychology, 103*, 17-29.

- Janssen, R., De Boeck, P., Viaene, M., & Vallaey, L. (1999). Simple mental addition in children with and without mild mental retardation. *Journal of Experimental Child Psychology*, 74, 261-281.
- Kort, W., Schittekatte, M., Bosmans, M., Compaa, E. L., Dekker, P. H., Vermeir, G., & Verhaeghe, P. (2005). *Wechsler intelligence scale for children - third edition (Dutch version)*. Amsterdam: NIP.
- Kucian, K., Grond, U., Rotzer, S., Henzi, B., Schönmann, C., Plangger, F., Gälli, M., Martin, E., & von Aster, M. (2011). Mental number line training in children with developmental dyscalculia. *Neuroimage*, 57, 782-795.
- Landerl, K., Bevan, A., & Butterworth, B. (2004). Developmental dyscalculia and basic numerical capacities: a study of 8-9-year-old students. *Cognition*, 93, 99-125.
- Melby-Lervåg, M., & Hulme, C. (2013). Is working memory training effective? A meta-analytic review. *Developmental Psychology*, 49, 270-291.
- Mussolin, C., Mejias, S., & Noël, M. P. (2010). Symbolic and nonsymbolic number comparison in children with and without dyscalculia. *Cognition*, 115, 10-25.
- Noël, M. P., & Rousselle, L. (2011). Developmental changes in the profiles of dyscalculia: an explanation based on a double exact-and-approximate number representation model. *Frontiers in Human Neuroscience*, 5, 165.
- Passolunghi, M. C., & Lanfranchi, S. (2012). Domain-specific and domain-general precursors of mathematical achievement: A longitudinal study from kindergarten to first grade. *British Journal of Educational Psychology*, 82, 42-63.
- Passolunghi, M. C., & Siegel, L. S. (2004). Working memory and access to numerical information in children with disability in mathematics. *Experimental Child psychology*, 88, 348-367.

- Passolunghi, M. C., Vercelloni, B., & Schadee, H. (2007). The precursors of mathematics learning: working memory, phonological ability and numerical competence. *Cognitive Development*, 22, 165-184.
- Piazza, M., Izard, V., Pinel, P., Le Bihan, D., & Dehaene, S. (2004). Tuning curves for approximate numerosity in the human intraparietal sulcus. *Neuron*, 44, 547-555.
- Pickering, S., & Gathercole, S. (2001). *Working Memory Test Battery for Children (WMTB-C)*. London: Psychological Corporation.
- Ramani, G. B., & Siegler, R. S. (2011). Reducing the gap in numerical knowledge between low- and middle-income preschoolers. *Journal of Applied Developmental Psychology*, 32, 146-159.
- Raven, J. C., Court, J. H., & Raven, J. (1992). *Standard progressive matrices*. Oxford, UK: Oxford Psychologists Press.
- Reigosa-Crespo, V., Valdés-Sosa, M., Butterworth, B., Estévez, N., Rodríguez, M., Santos, E., ... Lage, A. (2012). Basic numerical capacities and prevalence of developmental dyscalculia: The Havana survey. *Developmental Psychology*, 48, 123-135.
- Rousselle, L., & Noël, M. P. (2007). Basic numerical skills in children with mathematics learning disabilities: a comparison of symbolic vs. non-symbolic number magnitude processing. *Cognition*, 102, 361-395.
- Schneider, W., Eschmann, A., & Zuccolotto, A. (2002). *E-prime reference guide*. Pittsburg, PA: Psychology Software Tools.
- Schuchardt, K., Gebhardt, M., Mäehler, C. (2010). Working memory functions in children with different degrees of intellectual disability. *Journal of Intellectual Disability Research*, 54, 346-353.
- Sekuler, R., & Mierkiewicz, D. (1977). Children's judgments of numerical inequality. *Child Development*, 48, 630-633.

Siegler, R.S. (2009). Improving the numerical understanding of children from low-income families. *Child Development Perspectives*, 3, 118-124.

Soltész, F., Szűcs, D., Szűcs, L. (2010). Relationships between magnitude representation, counting and memory in 4- to 7-year-old children: a developmental study. *Behavioral and Brain Functions*, 6, 13.

Swanson, H. L., & Jerman, O. (2006). Math disabilities: A selective meta-analysis of the literature. *Review of Educational Research*, 76, 249-274.

Swanson, L., & Kim, K. (2007). Working memory, short-term memory, and naming speed as predictors of children's mathematical performance. *Intelligence*, 35, 151-168.

Tellegen, P. J., Winkel, M., Wijnberg-Williams, B. J., & Laros, J. (1998). *Snijders-Oomen nonverbal intelligence test, SON-R 2.5-7. Manual & research report*. Lisse: Swets and Zeitlinger.

Van der Molen, M. J., Van Luit, J. E. H., Jongmans, M. J., Van der Molen, M. W. (2009). Memory profiles in children with mild intellectual disabilities: strengths and weaknesses. *Research in Developmental Disabilities*, 30, 1237-1247.

Van der Molen, M. J., Van luit, J. E. H., Van der Molen, M. W., Klugkist, I., & Jongmans, M. J. (2010). Effectiveness of a computerised working memory training in adolescents with mild to borderline intellectual disabilities. *Journal of Intellectual Disability Research*, 54, 433-447.

Vander Steene, G., & Bos, A. (1997). *Wechsler preschool and primary scale of intelligence - revised, Flemish-Dutch version*. Lisse: Swets & Zeitlinger.

Wechsler, D. (1992). *Wechsler Intelligence Scale for Children – 3rd UK Edition (WISC-III UK)*. London: Psychological Corporation.

Wilson, A. J., Revkin, S. K., Cohen, D., Cohen, L., & Dehaene, S. (2006). An open trial assessment of “The Number Race”, an adaptive computer game for remediation of dyscalculia. *Behavioral and Brain Functions*, 2(20), 1-16.

Xu, F., & Arriaga, R. I. (2007). Number discrimination in 10-month-old infants. *British Journal of Developmental Psychology*, 25, 103-108.

Table 1

Descriptive statistics of the sample

Group	n	Sex	Age in years	Math ability ^a	IQ ^b
MID	31	17 boys, 14 girls	8.39 (0.83)	5.94 (3.24)	67.06 (5.22)
AL	31	12 boys, 19 girls	6.59 (0.35)	7.55 (2.47)	103.55 (7.02)
CA	31	15 boys, 16 girls	8.53 (0.36)	19.68 (4.11)	105.84 (6.45)

Note. ^a Number of correctly solved addition problems on Tempo Test Arithmetic. ^b For children with MID: IQ-score retrieved from school records; for the control children: IQ-score on Raven's Standard Progressive Matrices. MID = Mild Intellectual Disabilities; AL = Ability Level matched control group; CA = Chronological Age matched control group. Standard deviations are presented in parentheses.

Table 2

Correlations between working memory, numerical magnitude processing and mathematics in children with MID (n = 31)

	1	2	3	4	5	6	7
1. Tempo Test Arithmetic							
2. Digit Span Forward	.21						
3. Corsi Block	.24	.01					
4. Digit Span Backward	.53**	.33	.24				
5. Symbolic accuracy	-.07	-.03	-.05	.06			
6. Symbolic reaction time	-.42*	.05	-.24	-.13	-.04		
7. Non-symbolic accuracy	-.09	.11	-.10	.01	.56**	-.14	
8. Non-symbolic reaction time	.07	-.35	.03	-.04	-.08	.08	-.62**

Note. * $p < .05$; ** $p < .01$.

Table 3

Regression analysis predicting arithmetical ability in children with MID

Dependent variable	Predictor	β	t	ΔR^2
Tempo Test Arithmetic	Digit Span Backward	0.48	3.28**	0.23
	Symbolic reaction time	-0.35	-2.36*	0.12

Note. * $p < .05$; ** $p < .01$. The regression model was significant, $F(2,28) = 9.34$, $p < .01$,

$R^2 = .40$.

Figure Captions

Figure 1. Mean accuracy on the numerical magnitude comparison tasks as a function of group. MID = Mild Intellectual Disabilities; AL = Ability Level matched control group; CA = Chronological Age matched control group. Error bars depict 1SE of the mean.

Figure 2. Mean adjusted reaction time (based on correct responses only) on the numerical magnitude comparison tasks as a function of group. MID = Mild Intellectual Disabilities; AL = Ability Level matched control group; CA = Chronological Age matched control group. Error bars depict 1SE of the mean.

Figure 3. Number of correctly recalled items on the working memory tasks as a function of group. MID = Mild Intellectual Disabilities; AL = Ability Level matched control group; CA = Chronological Age matched control group. Error bars depict 1SE of the mean.

Figure 1

Figure 2

Figure 3