Journal of Experimental Child Psychology 116 (2013) 707–727

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp

Transcoding abilities in typical and atypical mathematics achievers: The role of working memory and procedural and lexical competencies

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A R T I C L E   I N F O

Article history:
Received 1 August 2012
Revised 16 July 2013
Available online 3 September 2013

Keywords:
Number transcoding
Mathematics achievement
Mathematics difficulties
Working memory
Numerical lexicon
Arabic Syntax

A B S T R A C T

Transcoding between numerical systems is one of the most basic abilities acquired by children during their early school years. One important topic that requires further exploration is how mathematics proficiency can affect number transcoding. The aim of the current study was to investigate transcoding abilities (i.e., reading Arabic numerals and writing dictation) in Brazilian children with and without mathematics difficulties, focusing on different school grades. We observed that children with learning difficulties in mathematics demonstrated lower achievement in number transcoding in both early and middle elementary school. In early elementary school, difficulties were observed in both the basic numerical lexicon and the management of numerical syntax. In middle elementary school, difficulties appeared mainly in the transcoding of more complex numbers. An error analysis revealed that the children with mathematics difficulties struggled mainly with the acquisition of transcoding rules. Although we confirmed

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http://dx.doi.org/10.1016/j.jecp.2013.07.008

the previous evidence on the impact of working memory capacity on number transcoding, we found that it did not fully account for the observed group differences. The results are discussed in the context of a maturational lag in number transcoding ability in children with mathematics difficulties.

Introduction

Reading and writing numbers in different formats constitutes a milestone in the mathematics education of a child. This ability begins to develop before formal instruction, but it is one of the most difficult skills that children must acquire during primary school (Geary, 2000). The establishment of a link between verbal and Arabic numerical codes is known as number transcoding and is considered a basic numerical ability (Deloche & Seron, 1987).

Verbal number codes are a structured, language-specific system (Fayol & Seron, 2005) acquired concomitantly with other linguistic abilities during early development (Wiese, 2003). In contrast, Arabic notation is acquired later and requires more formal instruction (Geary, 2000). Because it represents quantities more economically, the Arabic code is the dominant numerical notation, and its acquisition constitutes one of the first major steps toward more complex arithmetic skills (Fayol & Seron, 2005; von Aster & Shalev, 2007). Transcoding abilities are predictive of later, more complex achievements in arithmetic (Moeller, Pixner, Zuber, Kaufmann, & Nuerk, 2011).

Cognitive models of number transcoding

Cognitive models of number transcoding can be categorized as semantic or asemantic according to the role they attribute to the semantic representation of the magnitude of numbers. Semantic models postulate that an abstract representation of quantity mediates the relationship between numerical comprehension and production mechanisms (McCloskey, 1992; McCloskey, Caramazza, & Basili, 1985).

Asemantic models, in turn, assume that the numerical magnitude is not necessarily accessed during number transcoding and that the conversion of numerical input into output is an algorithm-based procedure. These types of models were first proposed by Deloche and Seron (1987). Barrouillet, Camos, Perruchet, and Seron (2004) proposed a developmental, asemantic, and procedural transcoding (ADAPT) model, which explains transcoding performance through the acquisition of procedural rules and lexical representations. The model predicts that complex and less familiar numbers rely more heavily on working memory capacity and on the application of procedural rules, whereas simpler and more familiar numbers are directly retrieved from the lexicon. ADAPT states that the expansion of the numerical lexicon and the compilation of a larger set of procedural rules account for the development of number transcoding.

The ADAPT model assigns a prominent role to working memory in numerical transcoding. Working memory is thought to be involved in the temporal storage of verbal information, lexical retrieval, and the execution of necessary manipulations. In fact, no other cognitive process has been so consistently associated with number transcoding performance and error patterns (Camos, 2008; Pixner et al., 2011b; Zuber, Pixner, Moeller, & Nuerk, 2009).

In the ADAPT model, working memory overload is considered one possible source of transcoding errors. It assumes that when the storage capacity of working memory is insufficient to handle the chain of digits, the transcoding process becomes prone to errors even if the necessary conversion rules are available (Barrouillet et al., 2004; Camos, 2008). Another important source of transcoding errors is the lack of transcoding rules. In this case, working memory resources are not directly involved because the storage capacity is not overloaded. These errors occur because low working memory capacity prevented the acquisition of sufficient knowledge about the transcoding rules. It is known that working memory plays a role in learning more complex rules throughout a child's school career (Camos, 2008), but this is a more indirect and long-term effect of working memory capacity on the development of number transcoding abilities.

Both working memory overload and the lack of transcoding rules are associated with specific patterns of transcoding errors attributable to the intrusion of 0s after the multiplicands. Errors in which the number of added 0s matches the magnitude of the multiplicands (e.g., 300070091 rather than 3791), called additive composition errors, occur when the transcoding rules have been acquired (i.e., Rule P2 prompts two empty slots and Rule P3 prompts three slots) but the storage capacity of the working memory has been overloaded. Computational simulations and group comparison studies have confirmed that these errors can be modulated by varying working memory resources (Barrouillet et al., 2004; Camos, 2008). Errors in which the number of added 0s does not match the multiplicand (e.g., 307091 or 300700091 rather than 3791) occur because the correct rule has not been acquired and a simpler one is used instead (e.g., Rule P3 prompts only two or more than three empty slots) and the number is built under a wrong digit frame.

The demand that number transcoding places on working memory capacity is strongly influenced by the complexity of the numerical syntax. Camos (2008) showed a consistent relationship among error rates, working memory capacity, and the quantity of rules in a study with second graders. The children with a low working memory span had higher rates of errors, especially syntactic errors related to the misapplication of place-coding rules. Importantly, the error rates increased with syntactic complexity. Moreover, Zuber and colleagues (2009) investigated the relationship among syntactic complexity, spatial processing, and executive function in first graders in the specific case of the German inversion rule for two-digit numbers. Pixner and colleagues (2011b) confirmed the association between working memory demands and syntactic errors by comparing within-participants transcoding abilities using the two different verbal number systems in the Czech language. The first graders had higher general error rates using the inverted system, and the specific association between inversion-related syntactic errors and working memory using the inverted system cannot be explained by familiarity. In summary, these studies demonstrated that the role of working memory in numerical transcoding is related to syntactic complexity.

Number transcoding in children

Number transcoding is particularly difficult to learn when the structure of the Arabic or verbal numbering system is not clear (Deloche & Seron, 1987; Pixner, Moeller, Hermanová, Nuerk, & Kaufmann, 2011a). The difficulties are more apparent in adults with brain lesions and in young children who are not completely familiar with the place value system of Arabic notation (Camos, 2008; Deloche & Seron, 1982; Geary, 2000; Power & Dal Martello, 1990, 1997; Zuber, Pixner, Moeller, & Nuerk, 2009). In both Arabic number reading (Power & Dal Martello, 1997) and Arabic number writing (Power & Dal Martello, 1990), second graders mastered writing two-digit Arabic numbers but had difficulty in transcoding three- and four-digit numbers. Most of the children's difficulties with number writing and reading were related to numerical syntax. As shown by Seron, Deloche, and Noël (1992), transcoding performance improves between first and second grades, and the improvement is more pronounced in reading than in writing Arabic numbers. Moreover, a ceiling effect was observed among the third graders on both tasks; therefore, there was only a small amount of additional improvement.

Other studies corroborate nearly perfect transcoding of one- and two-digit numbers by second graders (Camos, 2008) and few problems in transcoding three- and four-digit numbers among third and fourth graders (Sullivan, Macaruso, & Sokol, 1996). Therefore, numerical transcoding abilities for numbers up to four digits appear to be fully achieved in typically developing children after 3 years of formal education (Noël & Turconi, 1999).

Number transcoding and mathematics achievement

Mathematics learning difficulties (Mazzocco, 2007) have been associated with a deficit in number processing and calculation, and they have lifelong consequences for occupational attainment and psychosocial adaptation (Parsons & Bynner, 1997). The impact of this deficit on transcoding abilities has been investigated in only a few studies.

Geary, Hoard, and Hamson (1999) and Geary, Hamson, and Hoard (2000) found a small but significant association between the mathematics achievement of first graders and their performance in reading and writing one- and two-digit Arabic numbers. Difficulties in transcoding have also been observed in children with dyscalculia (i.e., more severe and persistent mathematics learning difficulties) (Landerl, Bevan, & Butterworth, 2004; Rousselle & Noël, 2007).

Importantly, these studies concentrated on items with a low degree of syntactic complexity (one- and two-digit numbers in Geary et al., 1999; two- and three-digit numbers in Landerl et al., 2004; one- to three-digit numbers in Rousselle & Noël, 2007). Therefore, differences in transcoding more complex items were not explored in these previous studies. A single study by van Loosbroek, Dirkx, Hulstijn, and Janssen (2009) compared the performances of 9-year-old children with and without arithmetic disabilities on a one- to four-digit Arabic number-writing task. These authors found significant differences between the two groups, even in one-digit number writing, with regard to the planning times but not the error rates.

Although previous studies were able to detect differences in transcoding abilities between groups of children with different levels of mathematics achievement, none of them analyzed children's performance during and after the initial schooling years in more depth. Furthermore, the deficit in numerical transcoding abilities found in children with differing levels of mathematics achievement (Geary et al., 1999; Landerl et al., 2004; van Loosbroek et al., 2009) has not been sufficiently explored with regard to the specific cognitive mechanisms that underlie these differences.

Interestingly, Geary and colleagues (1999) reported working memory differences between children with typical achievement in mathematics and children with mathematics difficulties (see Landerl et al., 2004). One might expect that the group differences in transcoding ability could be at least partially explained by differences in working memory capacity. According to the ADAPT model, working memory capacity is crucial for transcoding performance, specifically with regard to syntactic complexity and the strength of the lexical entries of individual items.

The current study

The aim of the current study was to investigate two transcoding routes (oral verbal to Arabic and Arabic to oral verbal) in Brazilian children with and without mathematics difficulties in early and middle elementary school (i.e., first/second grades and third/fourth grades, respectively). Because mathematics difficulties are generally associated with lower performance on numerical tasks (Landerl et al., 2004; Rousselle & Noël, 2007), we expected to observe higher error rates on both transcoding tasks among the children with mathematics difficulties in both early (Geary et al., 1999) and middle (van Loosbroek et al., 2009) elementary school. Moreover, we expected the error rates to be magnified with increasing numerical complexity.

Another aim of the current study was to determine the impact of working memory on the group differences on the transcoding tasks. If working memory capacity differs between typical achievers and children with mathematics difficulties, then numbers with higher syntactic complexity and weaker lexical entries would be associated with more pronounced group differences. Consequently, one would expect that by removing the effect of working memory, the differences in transcoding abilities would be reduced.

To shed light on the nature of the underlying difficulties, an analysis of the transcoding errors was performed. First, two broader classes of lexical and syntactical errors were considered in accordance with the taxonomy proposed by Deloche and Seron (1982). The group differences can be ascribed to the children's lexical knowledge of numbers, their understanding of Arabic syntax, or even both; these factors represent specific steps in the transcoding process defined by the ADAPT model. A higher frequency of lexical errors among the children with mathematics difficulties would indicate a basic deficit in the lexicon for numerical symbols. As previously hypothesized by some authors (Geary et al., 1999), children with mathematics difficulties may lack (or avoid) exposure to Arabic information, which is reflected in their poorly developed repertoire of numbers.

A higher frequency of syntactic errors is also expected in children with mathematics difficulties because previous evidence indicates the influence of the comprehension of base-10 syntax on mathematics achievement (Moeller et al., 2011). According to the ADAPT model, the pattern of syntactic errors in writing dictated Arabic numbers reflects both an overload of working memory resources and a lack of transcoding rules (Barrouillet et al., 2004; Camos, 2008). That is, if the group differences in number transcoding are the direct effect of the lower storage capacity of working memory in children with mathematics difficulties, then the specific syntactic errors mentioned above (additive composition) must be present. Otherwise, if the group differences are unrelated to the direct effects of working memory capacity, then one still can observe the syntactic errors that reflect the delay in the acquisition of transcoding rules among the children with mathematics difficulties (Camos, 2008).

Method

Participants

A total of 1007 children aged 7 to 12 years (Grades 1–6 in public and private elementary schools in the state of Minas Gerais, Brazil) were screened for arithmetic and spelling abilities (Brazilian School Achievement Test, Teste de Desempenho Escolar [TDE]; Stein, 1994). After obtaining written informed consent from their parents or legal representatives, the screening test was administered in groups in school classrooms. A subsample of 266 children agreed to complete an individual assessment that included measures of number transcoding, general intelligence (Raven's Colored Matrices), working memory (Digit Span and Corsi Span), and other measures beyond the scope of the current study. We excluded from the study all of the children who performed below the 25th percentile on the spelling section of the TDE, the children with general intelligence below the 15th percentile, and the children with general intelligence above the 75th percentile (according to the manual's norms). Next, the children were divided into two groups according to their performance on the arithmetic section of the TDE. The children who scored below the 25th percentile on the arithmetic subtest were classified as "children with mathematics difficulties," and the children who scored above the 25th percentile constituted the "control" group. The children in grades above fourth grade were not included.

The final sample contained 109 participants (81 control children and 28 children with mathematics difficulties) with a mean age of 9 years 6 months (*SD* = 1 year 1 month). To investigate developmental changes, the children were also classified according to their grade in school. Two groups were formed: one group consisting of the younger participants from early elementary school (first and second graders; 29 control children and 10 children with mathematics difficulties) and the other group consisting of the older participants from middle elementary school (third and fourth graders; 52 control children and 18 children with mathematics difficulties).

The reasons for grouping children from different grades were 2-fold. First, based on the findings of previous studies (e.g., Seron et al., 1992), the older children were not expected to struggle with transcoding numbers up to four digits but rather were expected to reach a nearly perfect level of accuracy. The first and second graders, on the other hand, were expected to have difficulty in transcoding three- and four-digit numbers (Power & Dal Martello, 1990, 1997). We assumed that both groups would be homogeneous with regard to their number transcoding abilities. Furthermore, no systematic investigations of the transcoding performance of older children with atypical achievement in mathematics have been performed. Therefore, two groups with different levels of performance were contrasted in the current study.

Psychological assessment

Numerical transcoding measures

The Portuguese verbal code is similar to the English code (e.g., Wood, Nuerk, Freitas, Freitas, & Willmes, 2006). The lexical classes are units, decades, and particulars (from *onze* [eleven] to *quinze* [fifteen]). Unlike in English, 100 and 1000 are both designated by only one word in Portuguese (*cem* and *mil,* respectively). There is no inversion in the Portuguese number word system; the decades are always followed by the units, which are preceded by the connector *e* (and) (e.g., 21 is read *vinte e um* [twenty and one]). For three-digit numbers, the hundreds place is also connected to the decades or units by the connector *e* (e.g., 321 is read *trezentos e vinte e um* [three hundred and twenty and one]). The thousands place in four-digit numbers is directly connected to the hundreds (e.g., 4321 is read *quatro mil trezentos e vinte e um* [four thousand three hundred and twenty and one]), but when the hundreds are absent the *e* makes the connection between the thousands and the decades or units (e.g., 4021 is read as *quatro mil e vinte e um* [four thousand and twenty and one]).

Arabic Number-Reading Task. A total of 28 Arabic numbers with one to four digits were printed in a booklet and presented to the children one at a time. The children were instructed to read them aloud (see the item list in Appendix A). The three- and four-digit numbers were grouped into three categories according to their complexity, indexed by the number of transcoding rules established by the ADAPT model (the quantity of transcoding rules in each item is presented in Appendix A). The three- and four-digit numbers were chosen to avoid presenting numbers with very strong lexical entries and to maintain the focus on syntactic complexity. The internal consistency of the task was .92 (Kuder–Richardson Formula 20 for dichotomous scales).

Arabic Number-Writing Task. The item set was composed of 28 numbers with up to four digits (see Appendix B). The children were instructed to write down the Arabic numerals that corresponded to the dictated numbers. As in the Arabic Number-Reading Task, the items were grouped according to their complexity (specified in Appendix B). The internal consistency of the complete task was .93 (Kuder–Richardson Formula 20). The complexity of the items was similar on both the Arabic Number-Reading Task and the Arabic Number-Writing Task.

General school achievement and intelligence measures

School Achievement Test. The TDE (Oliveira-Ferreira et al., 2012; Stein, 1994) is the most widely used standardized test of school achievement in Brazil, and norms are available for first grade through sixth grade. The test comprises three subtests that measure basic skills: single-word reading (which was not used during the screening phase), single-word spelling, and arithmetic operations. The word spelling subtest consists of 34 dictated words with increasing syllabic complexity. The arithmetic subtest is composed of three simple oral word problems that require written responses and 45 basic arithmetic calculations of increasing complexity that are presented and answered in writing. The reliability coefficients (Cronbach's α) for the subtests were high (.94 for spelling and .93 for arithmetic; Stein, 1994). The children were instructed to complete as many items as they could, and there were no time limits. The TDE may be considered the Brazilian equivalent to instruments available in other countries such as the Wide Range Achievement Test (Jastak & Wilkinson, 1984).

Raven's Colored Matrices. General fluid intelligence was assessed using the age-appropriate, Brazilian-validated version of Raven's Colored Matrices (Angelini, Alves, Custódio, Duarte, & Duarte, 1999). The analyses were based on *z*-scores calculated from the norms listed in the manual.

Working memory measures

Digit Span Task. The backward Digit Span Task was used to assess working memory, following the procedures of the Brazilian version of the Wechsler Intelligence Scale for Children-III (Figueiredo, 2002).

Corsi Block Tapping Task. To assess the visuospatial component of working memory, the backward Corsi Block Tapping Task was used, following the procedure used by Kessels, van Zandvoort, Postma, Kapelle, and de Haan (2000).

Table 1
Descriptive statistics and achievement on general neuropsychological measures for both groups.

	Controls ($n = 81$)		Children with mathematics difficulties ($n = 28$)		χ^2	*df*	*p*	–
Sex (% female)	55.6		64.3		0.65	1	.42	
School type (% public)	11.1		14.3		0.20	1	.91	
	Mean	*SD*	Mean	*SD*	*t*	*df*	*p*	*d*
Age (months)	115.25	12.72	113.11	16.15	0.71	107	.48	0.16
Raven (*z*-score)	0.36	0.61	0.37	0.66	−0.11	107	.915	0.02
TDE Arithmetic	16.44	5.81	9.57	5.65	5.43	107	<.001	1.21
TDE Spelling	25.40	6.22	18.89	10.00	3.23	107	.003	0.89
Digit Span (backward)	3.27	0.84	2.82	0.82	2.47	107	.015	0.54
Corsi Span (backward)	4.17	1.03	3.86	0.97	1.41	107	.16	0.51

Note: df, degrees of freedom; *d*, Cohen's effect size.

Results

Descriptive data

The control group and the children with mathematics difficulties did not differ significantly with regard to gender, school type (public or private), or age. The mean intelligence scores were also comparable across the children with mathematics difficulties and the control group (Table 1).

On the Arabic Number-Reading Task, 63% of the control group and 39.3% of the children with mathematics difficulties achieved the maximum score. On the Arabic Number-Writing Task, 50.6% of the control group and 42.9% of the children with mathematics difficulties did not commit any transcoding errors on the entire set of items (one- to four-digit numbers; see Appendixes A and B). Because of the small number of errors committed with one- and two-digit numbers, these items were dropped from further statistical analyses.

Group, item, and task influences on number transcoding

To investigate the influence of mathematics achievement, schooling, numerical complexity, and the transcoding route on error rates, we ran a mixed $3 \times 2 \times 2$ analysis of variance (ANOVA) for each education level separately. This design included the between-participants factor of group (control children or children with mathematics difficulties) and the within-participants factors of the transcoding route (error rates for the Arabic Number-Writing Task or the Arabic Number-Reading Task) and numerical complexity (error rates for each of the three levels of syntactic complexity). In all of the cases in which the assumption of sphericity was not satisfied, the Greenhouse–Geisser correction was applied. To approximate a normal distribution more accurately, the error rates were arcsine-transformed.

Fig. 1 depicts the effects of these three factors on the error rates. Among the children in early elementary school, the children with mathematics difficulties exhibited a higher overall error rate compared with the control children, and more errors were observed on the Arabic Number-Writing Task (Table 2). Numerical complexity also influenced the error rates, as shown by the main effect of complexity. Post hoc tests revealed significant differences between low and moderate complexity ($p < .001$) and between moderate and high complexity ($p < .001$).

In the middle elementary school grades, the children with mathematics difficulties still exhibited higher error rates, particularly when transcoding more complex numbers (moderate and high complexity; Table 2); the group differences increased with syntactic complexity (Fig. 1). Post hoc tests revealed significant differences between low and moderate complexity ($p < .001$; Fig. 1) and between moderate and high complexity ($p < .001$; Fig. 1). The effect of the transcoding route was not significant in middle elementary school.

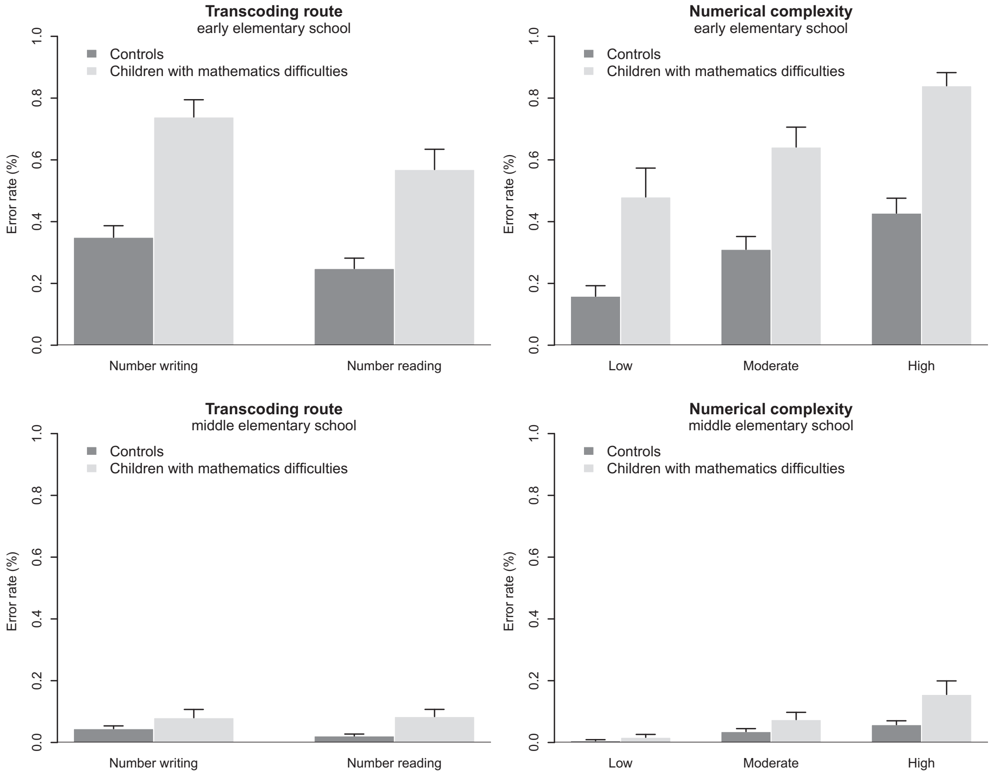

Fig. 1. Error rates as a function of task, numerical complexity, and children's group. Vertical bars depict standard errors.

In summary, the children with mathematics difficulties in first through fourth grades clearly struggled to write and read Arabic numbers. The overall performance on both transcoding tasks was influenced by the level of numerical complexity. Moreover, the group differences in later grades increased with numerical complexity; the differences were larger for more complex numbers. Next, the impact of working memory capacity on the interaction between children's mathematics abilities and the item complexity was assessed.

Working memory analysis

The control children had higher verbal but comparable nonverbal working memory capacity compared with the children with mathematics difficulties (Table 1). Consistent with previous reports (Barrouillet et al., 2004; Camos, 2008; Zuber et al., 2009), the error rates on the Arabic Number-Writing Task were moderately correlated with both the Digit Span ($r = -.34$, $p < .01$) and Corsi Block scores ($r = -.30$, $p < .01$). On the Arabic Number-Reading Task, these correlations were slightly weaker (Digit Span: $r = -.26$, $p < .01$; Corsi Block: $r = -.23$, $p < .01$) but still significant. The correlation between the two working memory measures was not significant ($r = .08$, $p > .05$). The absence of a correlation between the different components of working memory has also been reported in previous studies (Anguera, Reuter-Lorenz, Willingham, & Seidler, 2010; Passolunghi & Siegel, 2004) and can be attributed to the effect of the different type of information that must be recalled in each task (verbal vs. numerical).

To further explore the role of working memory in numerical transcoding, we created a series of stepwise regression models with the transcoding error rate as a criterion variable and age,

Table 2
Repeated-measures ANOVAs and ANCOVAs on transcoding error rates according to school level.

	Early elementary school						Middle elementary school					
	F (*df*)	MSE	η_p^2	*F* (*df*) (WM)	MSE (WM)	η_p^2 (WM)	*F* (*df*)	MSE	η_p^2	*F* (*df*) (WM)	MSE (WM)	η_p^2 (WM)
Numerical complexity	31.02 (2, 74)	0.45	.45***	3.53 (2, 70)	0.05	.09*	25.19 (2, 136)	0.08	.27***	1.40 (2, 132)	0.00	.02
Task	19.11 (1, 37)	0.22	.34***	6.80 (1, 35)	0.07	.16*	0.44 (1, 68)	0.00	.01	0.79 (1, 66)	0.00	.01
Group	13.69 (1, 37)	1.53	.27***	6.44 (1, 35)	0.61	.15**	6.89 (1, 68)	0.05	.09**	6.07 (1, 66)	0.05	.08*
Complexity vs. group	0.84 (2, 74)	0.01	.02	0.43 (2, 70)	0.01	.01	5.57 (2, 136)	0.02	.07**	4.82 (2, 132)	0.01	.07*

Note: WM, *F*, partial eta-squared, and significance values controlling for working memory differences; *df*, degrees of freedom.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

intelligence, and verbal and visuospatial working memory components as predictors. In early elementary school, the ability to write Arabic numbers was predicted by the verbal component of working memory and intelligence (R^2 = .39, adjusted R^2 = .36, βs = –0.45 and –0.32, respectively), whereas intelligence was the only reliable predictor for the score on the Arabic Number-Reading Task (R^2 = .23, adjusted R^2 = .20, β = –0.48). In middle elementary school, none of the regression models reached statistical significance.

Lastly, both the verbal (backward Digit Span) and nonverbal (backward Corsi Block) components of working memory were simultaneously included as covariates in the ANOVA model reported in the previous section. As shown in Table 2 (column "η_p^2" for the uncorrected values and column "η_p^2 (WM)" for the values after controlling for working memory effects), the effect size of the factor group was reduced slightly for the early elementary school children but remained the same for the children in middle elementary school. The interaction between group and numerical complexity, which was initially observed only in middle elementary school children, remained significant after removing the variance in working memory capacity. Importantly, the main effect of number complexity was substantially reduced in early elementary school children and completely eliminated in middle elementary school children.

In summary, number transcoding performance was clearly influenced by working memory capacity. However, the group differences observed in number transcoding could not be fully explained by the differences in working memory. Interestingly, working memory capacity was closely related to the transcoding of numbers at different complexity levels.

Error analysis

In this section, the errors committed in the Arabic Number-Writing Task and the Arabic Number-Reading Task are explored separately. The lexical and syntactic errors are investigated first, followed by an analysis of the specific patterns of syntactic errors.

Lexical errors occur when a lexical element is replaced by another one (e.g., Number Writing: *quarenta e seis* [forty-six] → 45; Number Reading: 13 → *quatorze* [fourteen]). A syntactic error is made when the lexical elements are correctly recovered but wrongly allocated in the numerical sequence (e.g., Number Writing: *cento e trinta e dois* [one hundred thirty-two] → 123; Number Reading: 5962 → *cinco mil seiscentos e noventa e dois* [five thousand six hundred ninety-two]) or when the overall numeric magnitude is modified even though the lexical units are correct (e.g., Number Writing: *mil e trezentos* [one thousand three hundred] → 1000300; Number Reading: 1900 → *dezenove mil* [nineteen thousand]).

Table 3
Error frequency as a function of school level, error category, and number of digits.

Grade	Error category (quantity of digits)	Number writing		Number reading	
		Controls	Children with MD	Controls	Children with MD
Early elementary school	Lexical (1- and 2-digit numbers)	4 (0.14)	9 (0.9)	0 (0.0)	4 (0.4)
	Syntactical (1- and 2-digit numbers)	1 (0.03)	5 (0.5)	0 (0.0)	2 (0.2)
	Lexical (3- and 4-digit numbers)	7 (0.24)	13 (1.3)	4 (0.14)	0 (0.0)
	Syntactical (3- and 4-digit numbers)	124 (4.27)	53 (5.3)	75 (2.59)	37 (3.7)
Middle elementary school	Lexical (1- and 2-digit numbers)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
	Syntactical (1- and 2-digit numbers)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
	Lexical (3- and 4-digit numbers)	9 (0.17)	2 (0.11)	2 (0.4)	0 (0.0)
	Syntactical (3- and 4-digit numbers)	77 (1.48)	36 (2.0)	8 (0.15)	14 (0.78)

Note: Numbers in parentheses represent the mean error frequencies (absolute frequencies/*n*).
MD, mathematics difficulties.

On both tasks, syntactic errors were the most frequent (87% of all errors on the Number-Writing Task and 93% of all errors on the Number-Reading Task; Table 3). There were differences in the relative frequencies of errors committed by the control children and the children with mathematics difficulties. Importantly, these differences were more evident among the early elementary school children and in the transcoding of three- and four-digit numbers. The error rates for one- and two-digit numbers were rather low, and neither of the middle elementary school groups committed errors transcoding these numbers. Accordingly, only three- and four-digit numbers were considered in the subsequent analyses.

Error analysis for Arabic Number-Reading Task

A 2×2 repeated-measures ANOVA was conducted separately for each school level using lexical and syntactic errors as the within-participants factors and group as the between-participants factor. For both school levels, similar main effects and interactions were observed. Syntactic errors were more frequent (93% of all classified errors; Table 4A), as the main effect of error category shows. Moreover, the main effect of group and its interaction with the error category revealed that the group differences were restricted to syntactic errors. Importantly, both the main effect and the interaction remained significant even after removing the variance in working memory. Lastly, the correlation coefficients showed that syntactic errors were correlated with both the visuospatial ($r = -.26$, $p < .01$) and verbal ($r = -.22$, $p < .05$) components of working memory. Lexical errors, on the contrary, did not correlate with working memory (all $ps > .05$).

A more detailed analysis of syntactic errors was conducted, classifying the errors into the following categories: wrong multiplicand (e.g., 400 read as *four thousand*), fragmentation of the numerical chain (e.g., 567 read as *five and six and seven*), omission of elements (e.g., 1900 read as *nine hundred*), misplaced elements (e.g., 432 read as *four hundred and twenty-one*), and misplaced multiplicand (e.g., 160 read as *one hundred six*). A similar error classification system was previously used by Power and Dal Martello (1997). The selection of the wrong multiplicand constituted the majority of syntactic errors (62.1%), followed by errors in fragmentation (27.5%) and omission of an element (6.6%). The other two categories, misplaced multiplicands and misplaced elements, were rather infrequent (1.9% for both cases) and, therefore, were not included in further analyses.

A 3×2 repeated-measures ANOVA (Table 4B) with error type (wrong multiplicand or fragmentation or omission) as the within-participants factor and group as the between-participants factor was conducted for each school level. The analysis revealed main effects of error category and group among the children in early and middle elementary school. A significant interaction between these two factors was observed; the group differences in wrong multiplicand errors were significant (early elementary school: $t(37) = -2.38$, $p = .039$; middle elementary school: $t(68) = -2.38$, $p = .029$), but the differences in fragmentation and omission errors were not significant (all $ps > .05$). For the two school levels, the main effect of group remained significant even after removing the influence of working memory in the analysis of covariance (ANCOVA). Moreover, working memory capacity fully accounted for the main effect of error category. Interestingly, the only error type that was correlated with working memory was fragmentation, which had a weak correlation with the visuospatial component of working memory ($-.23$, $p < .05$).

The analyses of the errors committed on the Arabic Number-Reading Task revealed two main findings. First, in both early and middle elementary school, children with mathematics difficulties struggle with numerical syntax, especially with assigning the correct values to the multiplicands (hundreds and thousands). Second, the achievement deficit cannot be fully explained by working memory capacity. The only errors that can be related to working memory capacity are fragmentation errors, which showed similar frequencies in both groups.

Error analysis for Arabic Number-Writing Task

A 2×2 repeated-measures ANOVA was conducted separately for each school level using lexical and syntactic errors as the within-participants factors and group as the between-participants factor. The analyses of the data from the children in early elementary school revealed a higher frequency of syntactic errors than lexical errors (87% vs. 12%) and a higher frequency of overall errors among

Table 4
Repeated-measures ANOVAs and ANCOVAs on transcoding error categories according to school level and task

	Arabic number writing						Arabic number reading					
	F (*df*)	MSE	η_p^2	F (*df*) (WM)	MSE (WM)	η_p^2 (WM)	F (*df*)	MSE	η_p^2	F (*df*) (WM)	MSE (WM)	η_p^2 (WM)
(A) Analysis of broader categories of lexical and syntactic errors												
Early elementary school												
Error category	59.76 (1, 37)	0.28	.62***	9.90 (1, 35)	0.05	.22**	26.59 (1, 37)	0.21	.42***	9.80 (1, 35)	0.07	.22**
Group	51.91 (1, 37)	0.25	.58***	36.68 (1, 35)	0.00	.51***	10.01 (1, 37)	0.08	.21**	5.38 (1, 35)	0.04	.13*
Error category vs. group	14.67 (1, 37)	0.07	.28***	8.91 (1, 35)	0.04	.20**	10.95 (1, 37)	0.08	.23**	6.01 (1, 35)	0.04	.15*
Middle elementary school												
Error category	98.91 (1, 68)	0.03	.59***	6.51 (1, 66)	0.00	.09*	16.34 (1, 68)	0.00	.19***	0.31 (1, 66)	0.00	.00
Group	28.67 (1, 68)	0.01	.30***	25.88 (1, 66)	0.01	.28***	12.42 (1, 68)	0.00	.15**	13.06 (1, 66)	0.00	.16**
Error category vs. group	37.29 (1, 68)	0.01	.35***	34.12 (1, 66)	0.01	.34***	13.31 (1, 68)	0.00	.16**	14.14 (1, 66)	0.00	.18***
(B) Analysis of syntactic errors												
Early elementary school												
Error category	34.10 (2, 74)	0.22	.48***	5.84 (2, 70)	0.04	.14*	7.57 (2, 74)	0.11	.17**	1.68 (2, 70)	0.02	.05
Group	47.93 (1, 37)	0.22	.56***	33.17 (1, 35)	0.13	.49***	19.93 (1, 37)	0.16	.35***	13.30 (1, 35)	0.1	.27**
Error category vs. group	12.20 (2, 74)	0.08	.25***	7.61 (2, 70)	0.05	.18*	4.24 (2, 74)	0.06	.10*	2.75 (2, 70)	0.04	.07
Middle elementary school												
Error category	2.44 (2, 136)	0.00	.04	0.18 (2, 132)	0.00	.00	15.11 (2, 136)	0.00	.18***	0.36 (2, 132)	0.00	.00
Group	10.52 (1, 68)	0.00	.13**	9.32 (1, 66)	0.00	.12**	12.57 (1, 68)	0.00	.16**	11.89 (1, 66)	0.00	.15**
Error category vs. group	1.27 (2, 136)	0.00	.02	1.35 (2, 132)	0.00	.02	12.01 (2, 136)	0.00	.15***	12.39 (2, 132)	0.00	.16**
(C) Analysis of "0"-related errors in Arabic Number-Writing Task												
Early elementary school												
Error category	14.76 (1, 37)	0.05	.28***	0.53 (1, 35)	0.00	.01	–	–	–	–	–	–
Group	18.72 (1, 37)	0.09	.34***	11.94 (1, 35)	0.00	.25**	–	–	–	–	–	–
Error category vs. group	6.36 (1, 37)	0.02	.15*	6.54 (1, 35)	0.02	.16*	–	–	–	–	–	–

Note: WM, *F* value, partial eta-squared, and significance values controlling for working memory differences; *df*, degrees of freedom.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

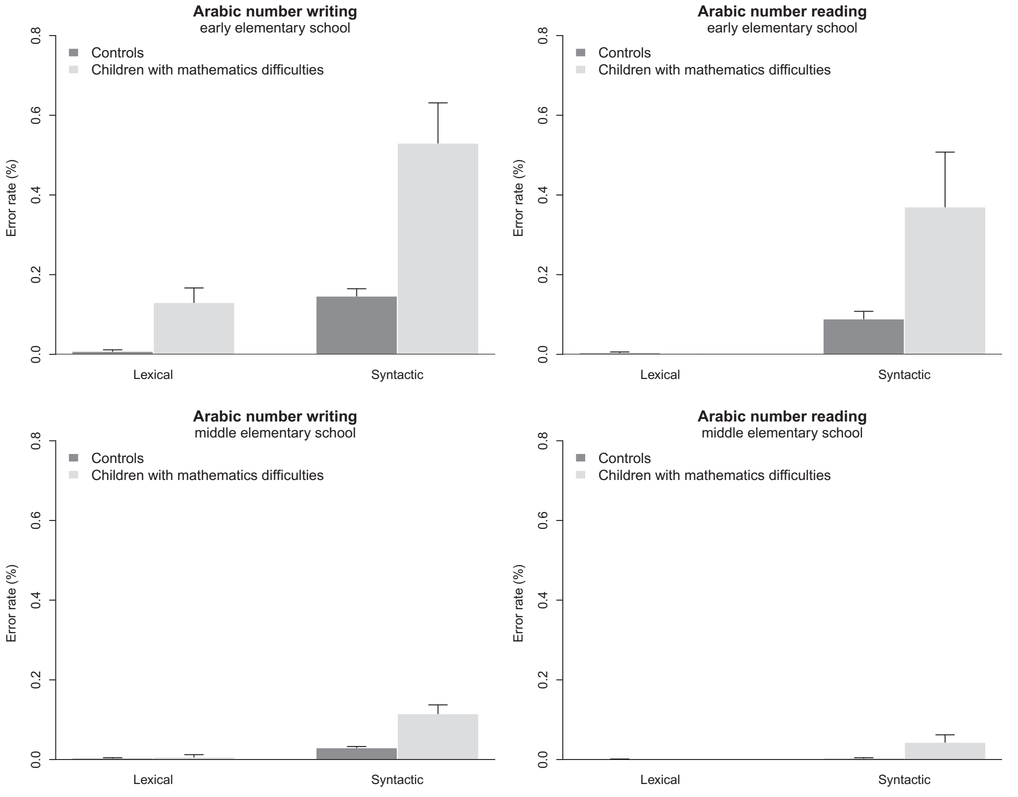

Fig. 2. Relative frequency of lexical and syntactical errors according to children's group and transcoding task. Vertical bars depict standard errors.

the children with mathematics difficulties (Table 4A). A significant interaction was also found; the frequency of errors in each category changed according to group. Post hoc tests revealed significant group differences in both lexical and syntactic errors (all *ps* < .01; Fig. 2), but the effect size was larger for the difference in syntactic errors (Table 4A). Among the middle elementary school children, a very similar pattern was found, but the post hoc tests for the group versus error category interaction were significant for syntactic errors, $t(68) = -3.638$, $p < .01$, and not for lexical errors, $t(68) = -0.697$, $p = .48$.

After removing the variance in working memory from these analyses, the main effects and interaction reported above remained significant but decreased for both school levels (Table 4A). Interestingly, the group differences decreased the least, whereas the effects of error category were more strongly affected (Table 4A). As a complement to these analyses, we investigated the correlations between the error types. Lexical and syntactic errors were significantly correlated with the verbal and visuospatial components of working memory. The verbal component correlated with lexical ($r = -.21$, $p < .05$) and syntactic errors ($r = -.27$, $p < .01$), whereas the visuospatial component correlated only with syntactic errors ($r = -.26$, $p < .01$).

The results presented so far suggest that during the early years of school, children with mathematics difficulties struggle with both lexical and syntactic properties of Arabic number writing, whereas children without mathematics difficulties experience difficulties only with syntax. In middle elementary school, a shift occurs; syntax becomes the only source of errors for children with mathematics difficulties, and children without mathematics difficulties seem to have mastered Arabic number writing. As we observed in the investigation of Arabic number reading, working memory capacity cannot fully account for the difference between the two groups.

Because of their high frequency, the syntactic errors were analyzed in greater depth. These errors were classified into different categories to provide a deeper understanding of the underlying nature of syntactic errors. They were classified into three main categories: intrusion of elements in the number (e.g., 700 written as 7003), omission of elements (e.g., 1015 written as 15), and misplaced elements (e.g., 3791 written as 3719). The majority of the errors were attributable to the intrusion of elements in the number (65.8%), followed by the omission of elements (23%) and misplaced elements (11.3%).

A 3 × 2 repeated-measures ANOVA, using error category and group as factors, was conducted separately for each school level (Table 4B). Among the children in early elementary school, significant main effects of group and error category were found; intrusion errors caused the highest error rates, followed by omission errors and misplacement errors (post hoc tests revealed all $ps < .01$). Lastly, there was a significant interaction between error category and group. The groups differed in the rates of intrusion errors, $t(37) = -3.42$, $p < .01$, and omissions, $t(37) = -2.69$, $p = .02$, but not in the rate of misplacement errors, $t(37) = -1.79$, $p = .11$. For the children in middle elementary school, the same analysis revealed a main effect of group but no effect of error category and no interaction. Therefore, the subsequent analyses of the Arabic Number-Writing Task results considered only the children in early elementary school.

Intrusion errors in which the digit 0 was the main intruder were further analyzed because they are highly informative about the children's mastery of numerical syntax. In our sample, these errors represented nearly all of the errors related to the intrusion of digits (94.7%). Although the percentages of these errors were very similar in the two groups of children (95.5% in the control group and 93.0% in the group of children with mathematics difficulties), the relative frequency was significantly higher among the children with mathematics difficulties, $t(37) = -2.82$, $p = .02$. Intrusion errors were classified into three subcategories. The additive composition errors were used as an index for errors caused by a working memory overload. The errors in which the number of added 0s did not match the magnitude of the multiplicands, called wrong-frame errors, were used as an index for missing transcoding rules. Another subcategory we investigated comprised multiplicative composition errors (a 1 followed by two or three 0s acting as the intruder, e.g., 81000 rather than 8000). Along with additive composition, multiplicative composition constitutes one principle of the Arabic code.

The most frequent error was the wrong frame, which accounted for 68.4% of the syntactic errors (67.0% in the control group and 71.4% in the group of children with mathematics difficulties), followed by additive composition errors (29.3% overall, 29.7% in the control group, and 28.6% in the group of children with mathematics difficulties). Multiplicative composition errors were infrequent (2.3% overall, 2.2% in the control group, and 2.4% in the group of children with mathematics difficulties) and, therefore, were not considered further in the analyses.

A 2 × 2 repeated-measures ANOVA (Table 4C) on the relative frequency of these errors confirmed the higher frequency of wrong-frame errors (main effect of error class) and a higher frequency of overall errors in the children with mathematics difficulties (main effect of group). Interestingly, there were group differences in wrong-frame errors, $t(37) = -2.59$, $p = .028$, but not in the occurrence of additive composition errors, $t(37) = -1.76$, $p = .109$, as the significant interaction between these factors demonstrates.

After removing the variance in working memory from these analyses, the main effect of group and its interaction with error category remained significant. In contrast, the main effect of error category disappeared, confirming the assumption of the ADAPT model that most of the differences between additive composition and wrong-frame errors are attributable to the demand on working memory resources. In addition, we analyzed the relationship between the working memory components and the classes of syntactic errors. Additive composition errors were correlated only with the verbal component of working memory ($r = -.44$, $p < .01$), whereas wrong-frame errors did not correlate with either component of working memory.

Finally, the last step in the analysis of the errors on the Arabic Number-Writing Task is to investigate the position where the errors occurred in the number. A closer analysis of the wrong-frame errors revealed more errors in the thousands place of four-digit numbers (a total of 76 vs. 11 errors in the hundreds place of four-digit numbers and 22 errors in three-digit numbers), with higher rates among the children with mathematics difficulties, $t(37) = -3.45$, $p = .006$. The difference between the control children and the children with mathematics difficulties was attributable to the insertion of two 0s after the thousands place, $t(37) = -2.48$, $p = .03$, but not the insertion of four or more 0s, $t(37) = -1.19$, $p = .26$. In the hundreds place of four-digit numbers, no group differences were found (all $ps > .05$). In the hundreds place of three-digit numbers, the error rate was higher among the children with mathematics difficulties, $t(37) = -2.32$, $p = .04$, because the children inserted only one 0, $t(37) = -2.39$, $p = .04$, but not three or more 0s, $t(37) = 0.84$, $p = .407$. Therefore, one can assert that the wrong-frame errors by the children with mathematics difficulties occur mainly because they insert fewer digits than required by the multiplicand, suggesting the use of less sophisticated transcoding rules dedicated to smaller numbers.

In summary, the data presented show that a large portion of the errors on the Arabic Number-Writing Task occurred because of incorrect management of the numerical frame. In agreement with other studies, additive composition errors were more closely related to working memory resources, whereas the errors attributable to the wrong frame were independent of working memory. Interestingly, there were only group differences in the errors unrelated to working memory; therefore, these differences in number transcoding can be explained by the absence of more advanced transcoding rules.

Discussion

The current study produced new evidence about the development of number transcoding abilities in children and the roles of numerical complexity, working memory, and mathematics proficiency. First, the children who struggled to learn mathematics faced two-way difficulties in transcoding verbal and Arabic notations, not only during the early years of elementary school (first and second grades) but also in middle elementary school (third and fourth grades). Second, although working memory capacity accounted for the differences in the transcoding of more syntactically complex items, it did not fully account for the difference in the performances of the children with and without mathematics learning difficulties. Third, and more important, the deficit in the transcoding performance observed in children with mathematics difficulties was primarily attributable to missing transcoding rules and not only to an overload of working memory. These topics and others related to our results are discussed in more detail in the following sections.

Number transcoding and mathematics achievement

The main aim of the current study was to examine number transcoding abilities in children with different mathematics achievement profiles. Our results indicated lower transcoding abilities in children with mathematics difficulties in both of the grade levels we assessed, although the error rates were lower among the children in middle elementary school compared with the children in early elementary school. To our knowledge, this is the first thorough investigation of the number transcoding abilities of groups of children in different grades. Similar research in the past (Geary et al., 1999, 2000; Landerl et al., 2004; Rousselle & Noël, 2007) investigated only a limited range of numbers without focusing on developmental aspects and mathematics abilities.

Lexical primitives

Numerical syntax was the main source of the children's difficulties; syntactic errors accounted for approximately 90% of all the errors committed on the two transcoding tasks for both grade levels. The differences between the typical achievers and the children with mathematics difficulties, however, were not limited to syntax. In early elementary school, the children with mathematics difficulties exhibited problems that affected both the lexical and syntactic domains of Arabic number writing. For the control children, only numerical syntax caused transcoding errors. This result suggests that at the beginning of elementary school, the children with mathematics difficulties may have a poorly developed numerical lexicon that improves with education. We can assume that these children might generally avoid or have little exposure to numerical information and, therefore, might not be as familiar with Arabic notation as their typical peers. A similar assumption was made by Geary and colleagues (1999), but the current study is the first to explicitly reveal a deficit in the numerical lexicon of children with mathematics difficulties.

Production rules

In agreement with Camos (2008), error rates increased with transcoding rules. This effect was observed in early and middle elementary school, but it differed according to the children's proficiency in mathematics. In early elementary school, the effect of numerical complexity on error rates was balanced between the two groups, and the error rates increased with numerical complexity. In the higher grades, the error rates were generally smaller than in the lower grades. However, the control children gave an accurate performance regardless of numerical complexity, whereas the children with mathematics difficulties continued to demonstrate lower achievement in transcoding complex numbers. Therefore, in higher grades, the group differences increased with numerical complexity. The children with mathematics difficulties were able to overcome their initial difficulties with basic numerical syntax, but they still struggled to transcode syntactically complex numbers.

Importantly, the types of syntactic errors observed differed qualitatively between the control children and the children with mathematics difficulties. On the Arabic Number-Reading Task, errors attributable to the production of the wrong multiplicand (e.g., reading 567 as *five thousand sixty-seven*) occurred more often among the children with mathematics difficulties and were the main source of the group differences on this task. This error does not appear to depend on the children's working memory resources because it did not correlate with either component of working memory. The other frequently observed error, fragmentation, is a strategy that involves splitting an Arabic numeral into smaller parts that can be transcoded correctly. Children resort to this strategy when they have not properly acquired transcoding rules for larger numbers, and they break the number into smaller units that they can transcode correctly. This type of error can also be caused by high demands on working memory given that this class of error was significantly (but weakly) correlated with visuospatial working memory. Interestingly, the two groups of children did not differ in the prevalence of this error. Therefore, we can assume that the lack of specific rules for reading three- and four-digit Arabic numbers is the major reason why children with difficulties in mathematics are less able to read Arabic numbers correctly. In the age range we investigated, the working memory demands imposed by the Arabic Number-Reading Task appeared to be relatively low.

On the Arabic Number-Writing Task, two main types of syntactic errors were observed: additive composition and wrong-frame errors. The frequency of additive composition errors was similar in both groups. Based on previous studies on the nature of this error (Barrouillet et al., 2004; Camos, 2008), one can conclude that the lower level of success in number transcoding observed in children with mathematics difficulties is not attributable to an overload of working memory resources.

The main source of errors in this task, however, concerned the incorrect management of the number of digits after the multiplicand parts when 0s were added incorrectly, designated here as wrong-frame errors. According to the ADAPT model, the source of wrong-frame errors lies in the incorrect application of Rules P2 and P3 (i.e., not prompting two empty slots after the hundreds place or three slots after the thousands place, respectively); thus, this error serves as an index of missing transcoding rules. Wrong-frame errors were made more frequently by the children with mathematics difficulties; therefore, we can attribute their difficulty with number transcoding to poor knowledge of the rules.

While investigating the nature of the wrong-frame errors, we observed that in comparison with the control children, the children with mathematics difficulties were more likely to add only two digits after the thousands place in four-digit numbers (i.e., fewer digits than required by the multiplicand). This result suggests that these children have not yet acquired the rules for transcoding four-digit numbers and wrongly applied the rules dedicated to three-digit numbers. A smaller difference was also observed in the hundreds place of three-digit numbers, indicating that at least some of the children with mathematics difficulties still had not acquired the rules for transcoding three-digit numbers. An early understanding of the place-value concept indexed by transcoding tasks has been shown to predict later performance in addition operations in typically developing children until the third grade (Moeller et al., 2011).

In summary, the results presented in this study indicate a maturational lag in the development of number transcoding abilities in children with mathematics difficulties. Although both groups of children followed the same developmental course with the establishment of a numerical lexicon as the first step, followed by an understanding of syntax, the developmental trajectories were clearly not synchronized in the two groups. The children with mathematics difficulties appear to lag behind their peers in the control group. For example, whereas the children in the control group may have difficulties with numerical syntax, the children with mathematics difficulties still exhibit problems with the basic numerical lexicon. In middle elementary school, the children in the control group appeared to have mastered the abilities necessary to transcode four-digit numbers, whereas the children with mathematics difficulties were still in the process of acquiring the rules for transcoding more syntactically complex numbers. These observations should be confirmed in a longitudinal study or by tracking developmental changes by inspecting children in each grade separately.

Notably, the prominent role of the numeral 0 in the place-value system of the Arabic code and its impact on numerical complexity should also be discussed. It acts as a placeholder that indicates when a given power of ten is empty, and it may cause difficulty because no corresponding verbal form of the Arabic zero exists. In the current study, most of the syntactic errors and nearly all of the errors caused by the intrusion of a new digit involved the numeral zero. Some previous studies have addressed this issue. For example, zero imposes more difficulties when it plays a syntactic role (e.g., in the number 1503) than when it has a lexical role (e.g., in the number 1500) (Granà, Lochy, Girelli, Seron, & Semenza, 2003). Thus, the number 0, compared with the other digits, may require more time to understand and extra cognitive resources to be correctly employed in transcoding tasks.

Working memory

The current study provides further evidence for the impact of working memory on number transcoding. The central point of the current findings is that working memory capacity cannot fully explain the lower number transcoding performance by children with mathematics difficulties. We thoroughly controlled for working memory in the analyses, and a consistent finding was that the influence of working memory on number transcoding is rather selective. Our results showed that the effect of working memory is stronger for effects that reflect the complexity of Arabic numerals and that involve "online" manipulations of numerical units. The effects related to the knowledge of the specific procedures necessary for accurate manipulations, in contrast, were weakly affected by working memory resources. Interestingly, removing the variance in working memory had only a small impact on all of the group differences. Considering the source of the transcoding errors observed among the children with mathematics difficulties (discussed in the previous section), one can state that the poor rule knowledge, not low working memory resources, accounts for the group differences in number transcoding.

With regard to the transcoding errors, the correlation coefficients revealed that nearly every category of syntactic errors on the Arabic Number-Writing Task, besides those related to the acquisition of rules, was correlated with components of working memory. Interestingly, the verbal component of working memory had a larger effect, and it was consistently associated with different aspects of transcoding (both lexical and syntactic errors).

Camos (2008) and Zuber and colleagues (2009) argued that it is problematic to assess verbal working memory by means of the Digit Span Task because the numerical nature of this task may produce overestimates of the effects of verbal working memory on number reading and writing. However, previous studies have investigated verbal working memory in children with mathematics difficulties using both digit and letter/word span tasks. In general, these studies report very similar performance patterns in digit and letter/word span tasks in both dyscalculics and controls (Koontz & Berch, 1996; Landerl et al., 2004; Landerl, Fussenegger, Moll, & Willburger, 2009). These findings do not support the view of stimulus-driven inflation of the impact of verbal working memory on transcoding. Rather, they suggest that the verbal working memory capacity measured is probably not attributable to the numerical aspects of working memory tasks. In line with these findings, we would expect that in the current study, at least in part, the Digit Span scores would relate to every transcoding error committed when transcoding more complex numbers. This is not what we observed; instead, the Digit Span influenced only transcoding errors specifically related to working memory capacity. Digit Span scores did not relate to the errors involving rule knowledge. Although our results cannot be seen as definite arguments for the validity of the Digit Span Task as a measure of verbal working memory in children with mathematics difficulties, they may be considered as such because no better evidence of the contrary has been presented so far.

How can the current results be explained by the ADAPT model?

The current study was designed in accordance with the ADAPT model's predictions regarding the role of procedural rules and working memory in number transcoding, and in the end the results aligned well with the model. As predicted by ADAPT, the number of conversion rules was a reliable index of transcoding complexity. Even considering only complex numbers with three or four digits, the analysis of numerical complexity showed a clear increase in the error rates as the number of rules increased. This finding also held for the Arabic Number-Reading Task, suggesting that transcoding from Arabic to verbal oral is also a rule-based procedure.

Other advantages of ADAPT are that it accounts for both of the possibilities specified in our hypotheses about the sources of syntactic errors in children with mathematics difficulties and that it predicts qualitative differences in errors caused by working memory overload or missing transcoding rules. Various analyses showed that working memory abilities could not account for the differences observed between the children, and the error analysis revealed qualitative differences only in the error classes that were not expected to be related to a working memory overload or deficit but rather were expected to be related to the acquisition of transcoding rules. Furthermore, this finding was observed only among the children in the beginning of elementary school. In summary, the results effectively revealed a delay in the crucial acquisition of transcoding rules in children with mathematics difficulties.

Conclusion

The current study improves our understanding of the nature of the transcoding impairments exhibited by children with mathematics learning difficulties whose performance on a standardized mathematics achievement test fell below the 25th percentile. First, an early pattern of difficulty in establishing an Arabic numerical lexicon was observed. Second, previous developmental findings regarding the association between numerical complexity and working memory performance were extended to children with mathematics learning difficulties. Third, compared with the children in the control group, the children with mathematics difficulties demonstrated a specific pattern of syntactic errors (specifically, wrong-frame errors). Wrong-frame errors occur when the rules dedicated to transcoding three- and four-digit numbers are applied incorrectly; they indicate that these children have difficulty in acquiring more complex transcoding rules in addition to working memory limitations. Our data suggest that children with mathematics difficulties retain less complex transcoding rules and require more time to qualitatively comprehend more complex rules, leaving them one step behind their typical peers. Therefore, compared with the children in the control group, the children with mathematics difficulties appear to have a developmental delay in mastering numerical transcoding. Although previous studies have described the influence of this knowledge on arithmetic achievement, to our knowledge this is the first study to report a clear association between place-value understanding and low arithmetic performance. Thus, deficits in transcoding abilities are firmly established in the inventory of impairments that characterize mathematics learning difficulties and contribute to the variety and complexity of these difficulties. Lastly, if difficulties in learning transcoding are at least partially attributable to a developmental lag, then intervention efforts should concentrate on the early identification of children with transcoding difficulties.

Acknowledgements

This research was granted by CAPES/DAAD Probral Program, Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq, 307006/2008-5, 401232/2009-3), and Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG, APQ-02755-SHA, APQ-03289-10). Vitor G. Haase is supported by a CNPq fellowship (308157/2011-7). Guilherme Wood is supported by a FWF research project (No. P22577).

Appendix A

The 28 items from the Arabic Number-Reading Task according to ADAPT category, quantity of transcoding rules, and complexity level.

Item	Arabic number reading							
	Number	Category	Rule(s)	Complexity level	Missing	Error (raw)	Error rate: Controls[a]	Error rate: Mathematics difficulties group[a]
1	3	U	2	–	0	0	.00	.00
2	6	U	2	–	0	0	.00	.00
3	8	U	2	–	0	0	.00	.00
4	12	P	2	–	0	0	.00	.00
5	14	P	2	–	0	1	.00	.04
6	50	D	2	–	0	0	.00	.00
7	20	D	2	–	0	1	.00	.04
8	47	DU	2 (3)	–	0	0	.00	.00
9	15	P	2	–	0	2	.00	.07
10	92	DU	2 (3)	–	2	1	.00	.07
11	80	D	2	–	2	1	.00	.04
12	19	DU	2 (3)	–	0	2	.00	.07
13	105	HU	4	Moderate	2	4	.02	.11
14	800	UH	3	Low	5	6	.06	.18
15	160	HD	3	Low	2	6	.04	.14
16	2000	UM	3	Low	12	13	.10	.25
17	400	UH	3	Low	3	4	.02	.11
18	102	HU	4	Moderate	2	4	.02	.11
19	170	HD	3	Low	2	7	.06	.11
20	1004	MU	4	Moderate	3	15	.12	.25
21	432	UHDU	4 (5)	High	4	6	.05	.18
22	567	UHDU	4 (5)	High	4	6	.07	.11
23	1013	MP	4	Moderate	4	16	.14	.25
24	8304	UMUHU	7	High	8	26	.22	.50
25	1070	MD	4	Moderate	4	20	.15	.39
26	5601	UMUHU	7	High	7	31	.26	.57
27	1900	MUH	4	Moderate	4	16	.10	.39
28	5962	UMUHDU	6 (7)	High	6	23	.19	.46

Note: A description of each item according to its category (U, unit; P, particular; D, decade; H, hundred; M, thousand), quantity of transcoding rules (DUs specified when directly retrieved and algorithmically transcoded—within parentheses), and complexity level is shown. The "Missing" column represents missing data.

[a] Relative frequencies of error rates.

Appendix B

The 28 items from the Arabic Number-Writing Task according to ADAPT category, quantity of transcoding rules, and complexity level.

Item	Arabic number writing							
	Number	Category	Rule (s)	Complexity level	Missing	Error (raw)	Error rate: Controls[a]	Error rate: Mathematics difficulties group[a]
1	4	U	2	–	0	0	.00	.00
2	7	U	2	–	1	0	.00	.00
3	1	U	2	–	1	0	.00	.00
4	11	P	2	–	1	0	.00	.00
5	40	D	2	–	0	3	.00	.11
6	16	DU	2 (3)	–	0	0	.00	.00
7	30	D	2	–	0	3	.01	.07

(*continued on next page*)

Appendix B (*continued*)

Item	Arabic number writing							
	Number	Category	Rule (s)	Complexity level	Missing	Error (raw)	Error rate: Controls[a]	Error rate: Mathematics difficulties group[a]
8	73	DU	2 (3)	–	2	6	.04	.11
9	13	P	2	–	1	0	.00	.00
10	68	DU	2 (3)	–	1	6	.01	.18
11	80	D	2	–	1	1	.00	.04
12	25	DU	2 (3)	–	1	1	.00	.04
13	200	UH	3	Low	2	6	.05	.07
14	109	HU	4	Moderate	2	6	.02	.14
15	150	HD	3	Low	2	11	.05	.25
16	101	HU	4	Moderate	2	7	.02	.18
17	700	UH	3	Low	2	6	.02	.14
18	643	UHDU	4 (5)	High	5	13	.06	.29
19	8000	UM	3	Low	2	12	.09	.18
20	190	HD	3	Low	4	8	.05	.14
21	1002	MU	4	Moderate	2	25	.21	.29
22	951	UHDU	4 (5)	High	3	13	.06	.29
23	1015	MP	4	Moderate	2	22	.17	.29
24	2609	UMUHU	7	High	4	37	.28	.50
25	1300	MUH	4	Moderate	4	28	.22	.36
26	3791	UMUHDU	6 (7)	High	7	33	.28	.36
27	1060	MD	4	Moderate	5	31	.26	.36
28	4701	UMUHU	7	High	2	34	.25	.50

Note: A description of each item according to its category (U, unit; P, particular; D, decade; H, hundred; M, thousand), quantity of transcoding rules (DUs specified when directly retrieved and algorithmically transcoded—within parentheses), and complexity level is shown. The "Missing" column represents missing data.

a

Relative frequencies of error rates.

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