Universidade Federal de Minas Gerais
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TRANSCODIFICAÇÃO NUMÉRICA EM CRIANÇAS E ADULTOS DE BAIXA ESCOLARIDADE: O PAPEL DA MEMÓRIA DE TRABALHO, CONSCIÊNCIA FONÊMICA E IMPLICAÇÕES PARA A APRENDIZAGEM DA MATEMÁTICA.

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Ouça: A maioria dos homens não quer nadar antes que o possa fazer. Não é engraçado? Naturalmente, não querem nadar. Nasceram para andar na terra e não na água. E, naturalmente, não querem pensar: foram criados para viver e não para pensar! Isto mesmo! E quem pensa, quem faz do pensamento sua principal atividade, pode chegar muito longe com isso, mas, sem dúvida estará confundindo a terra com a água e um dia morrerá afogado.

Herman Hesse

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RESUMO

Moura, R. (2014). Transcodificação numérica em crianças e adultos de baixa escolaridade: o papel da memória de trabalho, consciência fonêmica e implicações para a aprendizagem da matemática. Tese de doutorado, Programa de Pós-graduação em Neurociências, Instituto de Ciências Biológicas da Universidade Federal de Minas Gerais, Belo Horizonte.

O estabelecimento de um elo entre as notações numéricas verbal e Arábica, chamada transcodificação numérica (TN), constitui umas das habilidades numéricas mais elementares, adquiridas já nos primeiros anos de estudo. Apesar de ser considerada uma habilidade básica, a TN assume um papel de destaque no estudo da cognição numérica e da aprendizagem da matemática, uma vez que constitui um dos pilares sobre os quais serão desenvolvidas habilidades numéricas mais complexas, como o cálculo. O objetivo geral da presente tese é fazer uma investigação ampla das habilidades de TN em crianças em idade escolar e em adultos de baixa escolaridade, analisando os principais fatores cognitivos envolvidos. No estudo 1 é feita uma investigação das propriedades psicométricas de uma tarefa de escrita de números em crianças de 1ª à 4ª série do ensino fundamental, com ou sem dificuldades de aprendizagem da matemática. Apesar das baixas taxas de erros, a mesma se mostrou um instrumento consistente e altamente sensível para identificar crianças de 1ª e 2ª série que apresentam dificuldades de aprendizagem da matemática. No estudo 2, crianças de 1ª à 4ª realizaram tarefas de escrita e leitura de numerais Arábicos, além de tarefas de inteligência e memória de trabalho. Os resultados indicaram que as crianças com dificuldade na matemática apresentam um atraso na formação do léxico numérico e, ainda, uma dificuldade na aprendizagem da sintaxe do código Arábico, a qual se estende até a 4ª série do ensino fundamental. É importante notar que essas dificuldades não puderam ser explicadas por déficits na capacidade de memória de trabalho, sendo portanto, de caráter especialmente numérico. O estudo 3 explora o papel da consciência fonêmica na TN. Os resultados sugerem que a consciência fonêmica media a atuação da memória de trabalho na TN. O estudo 4 explora o efeito de fatores educacionais nas representações não-simbólicas e simbólicas, por meio do estudo de adultos semianalfabetos. De acordo com os resultados, as representações não-simbólicas de magnitudes se desenvolvem em adultos independentemente do nível de letramento. Além disso, ficou claro também que, em indivíduos que fazem parte uma sociedade industrializada, a ampliação do léxico numérico é um processo que acontece intuitivamente, ao passo que a aprendizagem da sintaxe numérica demanda uma educação formal, específica para tal. Finalmente, o trabalho constituiu uma evidência a mais para a hipótese de que a transcodificação é um processo cognitivo assemântico.

Palavras-chave: transcodificação numérica, aprendizagem da matemática, memória de trabalho.

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CHAPTER 1

GENERAL INTRODUCTION AND LITERATURE REVIEW.

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INTRODUCTION

The research on numerical cognition has achieved remarkable progress during the last two decades. Today much is known about the development, related capabilities and neural substrate of human representations of number. One of the central aspects on this research is how humans acquire and use the two symbolic systems dedicated to represent numbers: the visual-Arabic code, and the verbal number code. The present text will address these questions by conducting a literature review. In the next section, the two symbolic systems will be presented in detail, followed by numerical semantics, that is, the core magnitude information conveyed by these symbolic systems. Afterwards, the cognitive models of numerical cognition are going to be presented. Finally, the paper will review the theoretical and empirical literature about the translation between different symbolic representations, namely, number transcoding, focusing on the cognitive models and involved neuropsychological mechanisms.

Symbolic codes

The ability to use symbols to convey mental representations is one of the most remarkable landmarks in the evolution of human species. In the number domain, the development of symbolic systems to represent quantities allowed us to move far beyond approximation and to understand numbers with greater precision. There are two main symbolic systems intended to represent numerical information: the verbal-numerical and the visual-Arabic systems. Despite that both systems share the same goal, they work in very particular ways. The verbal system conveys numbers by means of phonological (oral) and verbal-written (orthographic) representations, while in the Arabic system numbers are represented as visual symbols. The next sessions will present these two systems in further detail.

The Verbal system

In every natural language there is a subsystem devoted to the expression of whole numbers by words and phrases. The verbal numeral system (henceforth number word system) is subject to the same variability as its host-language, so that there is no world-wide dominant number word system for numbers. Therefore, this system varies largely between different languages, and in some particular cases, also within the same language (e.g. in Czech, there are both a unit-decade inverted and a non-inverted system, as further discussed below).

The extension of the numerical lexicon is not constant across languages, and reflects the complexity of its counting system. In some native languages from Brazil and Australia, for instance, this lexicon does not go beyond 3 or 4, which are the largest numbers they count (Butterworth, Reeve, Reynolds, & Lloyd, 2008; Pica, Lemer, Izard, & Dehaene, 2004). Most modern languages, in turn, possess a complex counting system arranged in bases of power, which allows the counting of infinite quantities in an economic fashion. In these languages, the lexicon contains single words for all natural numbers up to its base number (10, in many cases), and for some round larger numbers, such as 20, 100 and 1000 (like *twenty*, *hundred* and *thousand* in English, and *vinte*, *cem* and *mil* in Portuguese).

Concerning the numerical syntax, according to Hurford (1987) in most languages it is constituted by relationships of addition and multiplication between the lexical units. When a numeral has two immediate constituents its numerical value is calculated by adding the values of its constituents (in English: *sixty-four* means 60 + 4). In some cases, like Portuguese, this addition operation is explicitly denoted by the connector “e” (*sessenta e quatro* means 60 + 4). In the Watchandie language from Western Australia, the lexicon comprises only *co-ote-on* (one) and *u-tar-ra* (two) (Tylor, 1891). In the need to refer to the numbers *three* and *four*, an operation of addition is applied: *u-tar-ra coo-te-oo* for the first, and *u-tar-ra u-tar-ra* for the last. The multiplication is a more complex syntactic operation, as it requires a numeral system organized in powers of bases. In these cases, when a numeral phrase has two immediate constituents, and the second one is a noun-like numeral representing a base (e.g.,-ty, thousand, hundred in English; -enta, -entos, mil, milhão, in Portuguese), the value is calculated by multiplying their values (in English *two hundred* means 2 x 10^2, and in Portuguese *três mil* means 3 x 10^3).

It is important to note that language-specific idiosyncrasies are observed in the syntax of many numerical systems. One of the most remarkable ones is the inversion between the order of units and decades in languages such as German, Dutch and Czech. The higher-before-lower ordering of the base numbers, that generates forms such as *sixty two* (60 + 2) in English and *sessenta e dois* in Portuguese, would wrongly generate *sechzig und zwei* in German (sechzig = 60, und = “and”, zwei = 2). In these languages, the numeral syntax requires the inversion of these bases in order to generate the proper form *zwei und sechzig*.

The Visual/Arabic system

The origins of the visual codes go back to the same time as when humans developed language and basic numerical abilities, such as numeration/counting (Ifrah, 1997). The rising of the numerical writing systems came from the necessity to store and share the results of any enumeration, without resorting to any verbal-oral representations. The very first method for keeping this information was the use of sets of concrete objects (e.g. bones, sticks or stones), or by notching pieces of bones or wood, matching the number of the to-be-counted set in a one-to-one correspondence (Dehaene, 2011; Ifrah, 1997). Despite providing a strategy to represent large quantities that could not be precisely grasped by human perceptual apparatus, this method failed when larger quantities needed to be represented.

The development of complex symbolic systems for numbers began with the elaboration of a lexicon, which is a set of symbols representing a finite number of smaller and some larger numbers, and a syntax, which allows the representation of larger numerals by the combination of the lexical items. In the Roman numerical system, for example, this lexicon was composed by only seven symbols: I (one), V (five), X (ten), L (fifty), C (hundred), D (five hundred) and M (thousand). Examples of written numerical systems with larger lexicons are the Hindu-Arabic (10 symbols) and Greek (27 symbols).

As in the number word system, the most basic syntactic mechanisms that allowed the combination of lexical items in the Arabic notation is the additive principle. It is the basic syntactic mechanism of the Roman numerical system. Instead of depicting the number 7 as IIIIIII, in Roman notation it can be achieved by simply summing the numbers 5 (V) and 2 (II), making VII. Furthermore, the Roman system also possess a subtraction principle in its syntax, which is applied when a smaller number appears on the left side of a higher number. For example, the number 4, which is achieve by subtracting 1 from 5 (IV). This is certainly a more economical method when compared to the iconic representations, in which larger numbers, such as 45, would become excessively long. Nevertheless, it is still not very practical, as larger numbers such as 48 (XLXVIII) still needs a long sequence of 6 digits in order to be represented, and some inconsistencies may occur, such as a smaller number (e.g. XXXVII - 37) being longer than a larger number (e.g. LI - 51). Moreover, the visual organization of Roman code does not allow any kind of calculation.

There are two main syntactic properties that allowed the development of more economic visual numerical systems: the place-value syntax and the establishment of a base number. According to the place-value principle the numerical value of a digit is given by its position in the number. The magnitude of the change from one position to the next is given by the power of a base number. In the Hindu-Arabic number system (henceforth referred to as Arabic number system) the base number is 10, and successive places in a number represents successive powers of base 10, from units (10^0), tens (10^1), hundreds (10^2) and so on. The number 291, for example, is composed by 2 hundreds (2×10^2), nine tens (9×10^1) and one unit (1×10^0), thus the value of a number is obtained by multiplying the digit by its corresponding power of base 10 (multiplicative principle). The overall magnitude of the number is given by the addition of each of these products ($291 = [2 \times 10^2] + [9 \times 10^1] + [1 \times 10^0] = 200 + 90 + 1$). As can be noted, in the visual system the operators are implicitly represented in the syntax, which constitutes a remarkable difference comparing to the Verbal code, where both operations are explicitly mentioned.

It is important to note that the Arabic number system was not the only one to employ the principles of place-value and base numbers (Ifrah, 1997). The Babylonians developed a numerical system whose base number was 60, and the Roman system had the base number 10 (10^0 = I, 10^1 = X, 10^2 = C, etc) and the sub-base 5 (5^1 X 10^0 = V, 5^1 X 10^1 = L, 5^1 X 10^2 = D).

One of the main advantages of the Arabic number system is the digit zero, an indispensable placeholder that indicates the absence of a given power of base in a multi digit numeral. For example, in the number 10 the 0 represents the absence of units (0 X 10^0), and in the number 407 it shows that there are no tens (0 X 10^2).

The Arabic number system is the most widely spread numerical system in modern societies. In fact, no other symbolic system (whether numeric or not) is so widely used as the Arabic number system. One can surely assert that the main reason for this acceptance lies in its simplicity in conveying numerical information, allowed by its relatively short lexicon of 10 elements together with its highly efficient syntax. Furthermore, one remarkable advantage of the Arabic number system is the simplicity with which it allows numerical operations.

As stressed before, the main purpose of any symbolic number system is to transmit numerical quantities. Currently, one of the most intriguing questions in the field of numerical cognition is how the human mind understands the meaning of the numbers. In the next section this topic will be addressed in deeper detail.

Numerical semantics: what does a number mean?

As in every other animal species, the human mind is devoid of any evolutionary acquired, built-in process that allows digital or discrete representations of numbers. In fact, symbolic systems are a very recent invention, and therefore they could not have influenced the evolution of our brain in such a way that they would become a built-in process (Dehaene & Cohen, 2007). In turn, the human brain is naturally endowed with a rudimentary number processor, that is, a biologically determined number knowledge which allows the representation of numbers.

The research on number processing has found that this pre-verbal number knowledge is constituted by two basic systems for numerosity encoding: the object-tracking system (OTS), and the approximate number system (ANS; Piazza, 2010). The OTS represents small numerosities up to 4 with high accuracy, while the ANS is responsible for the representation of larger numerosities analogically, and therefore, with increasingly imprecision.

Unfolding the psychological mechanisms with which numerical magnitudes are mentally encoded has been one of the main research topics in numerical cognition. A central concept which helped to make this issue clear is the mental number line (see Dehaene, 2011), which is understood as the medium on which numbers, as well as other non-numerical magnitudes such as time and space (Walsh, 2003), are represented.

The nature and functioning of the mental number line are still under debate, and one of the main questions is how it codes numerical information. According to one theory (place coding, by Dehaene & Changeux, 1993), each numerosity is represented by a noisy distribution of activation on an internal continuum growing from left to right, in a way that any given numerical magnitude (set of n visual objects) is mentally represented by a Gaussian distribution. Importantly, despite the fact that the means of each distribution increase with numerical magnitude, their standard deviation (w) is always constant. It is defined that the distances between successive distributions are logarithmic spaced, so that smaller numerosities activate less overlapping, thus more specific, representations (compressive coding). The model also postulates that numerical stimuli fire specific populations of neurons according to their numerical magnitudes, and because of the logarithmically compressed nature of coding, larger neuronal populations are dedicated to small numerosities.

This model has gained considerable prestige over time due to its capability to accommodate the classical psychophysical postulates of Weber and Fechner (Izard & Dehaene, 2008), as well as some important empirical findings. The Weber's law states that the minimal numerical change that can be discriminated increases in direct proportion to the magnitude of the numerosities (that is, it depends on the ratio between the magnitudes). Later, Fechner demonstrated that Weber's law could be accounted for by postulating that external numerosities are internally scaled into a logarithmic internal representation of sensation.

Consistent empirical findings that could be well described by this model are the distance and the size effects. The distance effect refers to the systematic decrease in numerosity discrimination performance as the distance between the magnitudes gets shorter. It has been consistently reported in various animal species (Gallistel & Gelman, 1992), and also in humans of different ages (Izard, Dehaene-Lambertz, & Dehaene, 2008). The size effect refers to the increasing difficulty in number processing tasks when the distance is kept constant, but the numerical magnitudes get larger.

These effects constitute strong evidence for elucidating the nature of mental representations of numerical magnitudes. They indicate that animals and humans "seems to possess only a fuzzy representation of numbers, in which imprecision grows proportionally to the number being represented" (Dehaene, 2011).

Cognitive models of number processing

Different cognitive models were proposed in the last two decades aiming at conciliating numerical semantics and the symbolic codes and their interactions. The two main cognitive models of numerical processing encompassed the Arabic and number word codes, as well as the numerical semantics. In the following, the Abstract Code model model of McCloskey (1992) and the Triple Code model of Dehaene (1992, 1995) shall be described.

The Abstract semantic model

The Abstract semantic model was proposed by McCloskey (1992), as a further elaboration of a previous model (McCloskey, Caramazza, & Basili, 1985). The model proposes a central semantic system, and subsystems dedicated to calculation as well as to Arabic and Verbal input (comprehension) and output (production, Figure 1). Based on the observation of double-dissociations in brain damaged patients, in which the processing of Arabic numerals was intact but the processing of verbal numerals was impaired (Anderson, Damasio, & Damasio, 1990; McCloskey, 1992), the pathways for Arabic and Verbal numerals processing are considered to be independent from each other. The Arabic and Verbal comprehension systems are responsible to convert the input from its original code, to a semantic abstract code, which is the same apart of the input's modality. The key aspect of this model is the existence of a semantic representation mediating every input and output from the Arabic and verbal codes. The numerical representation built by the semantic system is a decomposition of the inputs into their powers of ten following the place-value syntax of the Arabic code. For example, the semantic representation for the number 379 is built as {3} 10^2 {7} 10^1 {9} 10^0. This representation can either be send to the calculation subsystem, where arithmetic operations are performed, or to the Arabic and verbal production subsystems, where the semantic representation is transcoded to the expected output.

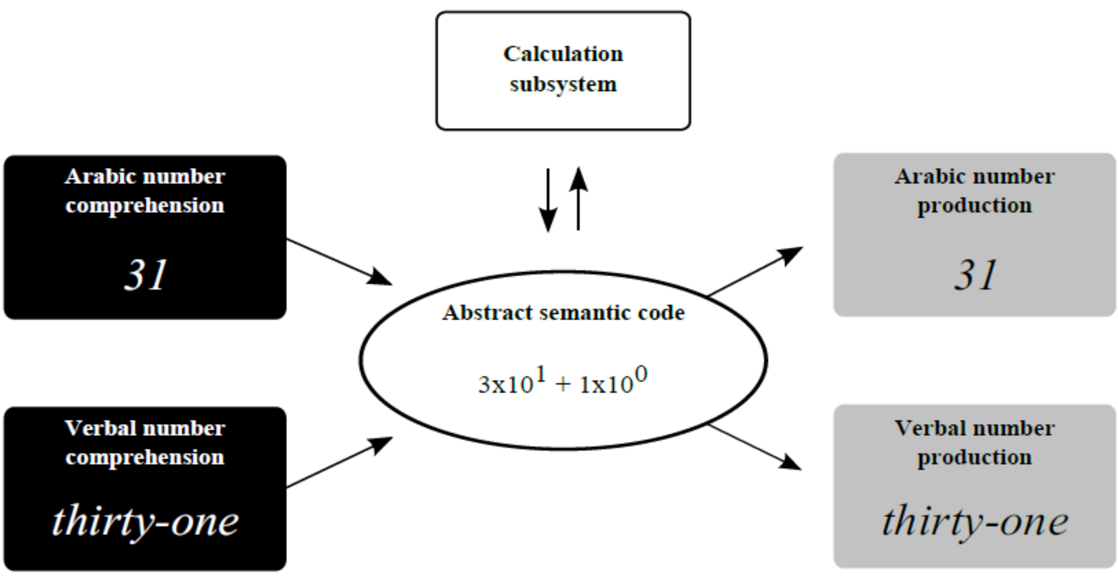

Figure 1 – Schematic view of the abstract semantic model.

Later on, a variant of the abstract-semantic model was proposed by Power and Dal Martello (1990), whose main modification was the assumption of a verbally structured semantic representation. This representation is build according to primitive numerical concepts that are organized according to their semantic meaning. For example, the semantic representation of 365 is built as (C3 * C100) + ((([C10 * C6)] + C5). Cipolotti and Butterworth (1995) made a final development of the semantic model after the study of a patient with serious difficulties in number writing and reading, but with spared calculation abilities. The abstract semantic model could not account for this performance profile. Thus the authors proposed a multiroute model for numerical processing, with an independent asemantic route (Figure 2).

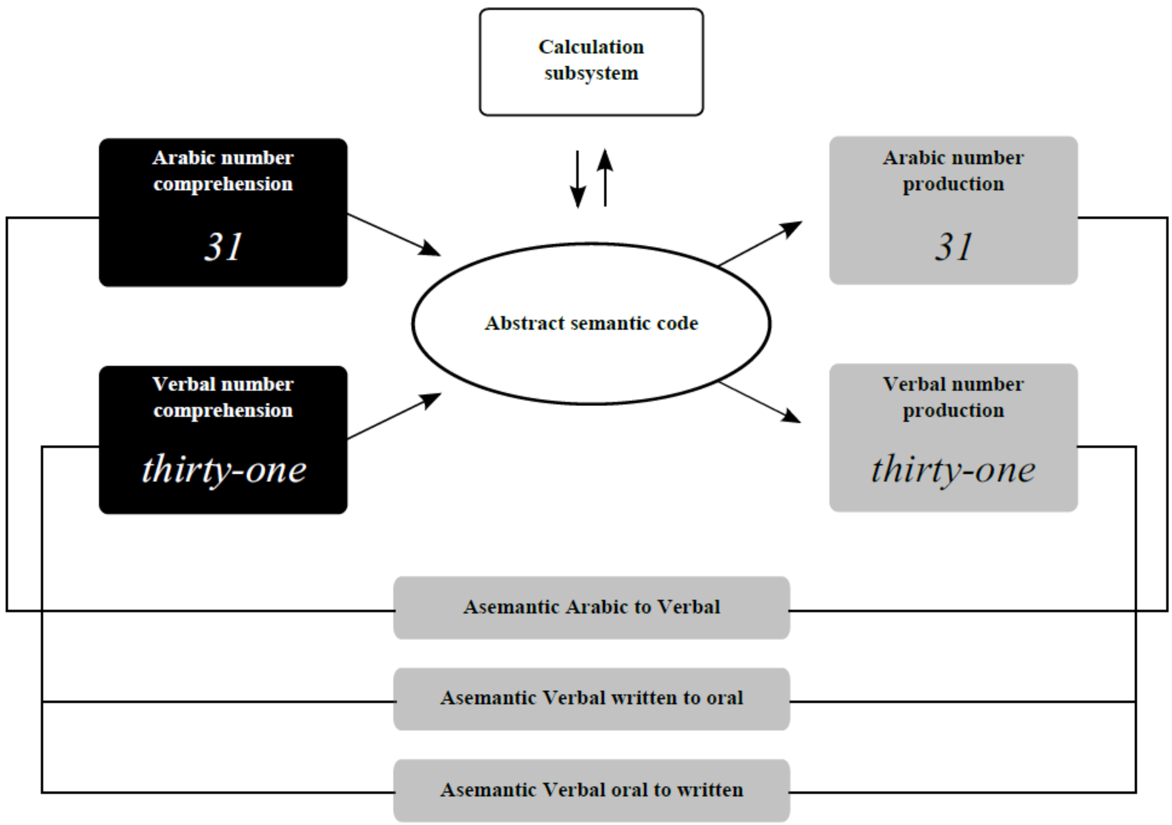

Figure 2 – Schematic view of the dual-route model of Cipolotti and Butterworth.

The Triple Code model

Progress in the understanding of numerical processing was propelled mostly by the latest cognitive model of numerical cognition, the Triple Code Model, developed by Stanislas Dehaene (Dehaene, 1992). The model postulates three numerical codes. An inherited abstract code, in which numerical information is represented as non-symbolic analogical magnitudes, that is, the core semantic meaning of a number. This code was formulated based on evidences that mental representations of numerical magnitudes are not exact, but only approximate. The other two codes involve the use of symbolic systems in order to convey numerical information (Figure 3). Contrary to the abstract semantic model of McCloskey, in the Triple code model there is no hierarchical organization between the different codes, that is, the semantic code does not work as a bottleneck whereby any input is mandatorily processed. Furthermore, in the Triple Code model the semantic value of a number is built under a representation independent of cultural tools (like the base 10 syntactic organization in the abstract semantic model), which allows a better understanding of its phylo- and ontogenetic course.

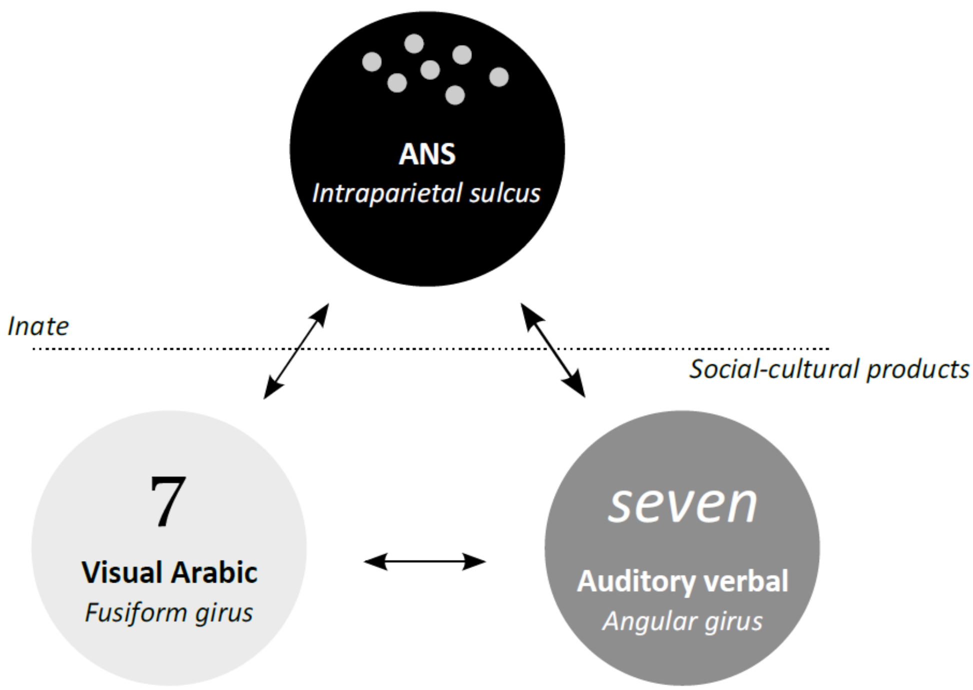

Figure 3 – Schematic view of the triple code model.

One of the most important achievements of the triple code model was the formulation of the neural underpinnings of the three kinds of numerical representations, by means of both neuropsychological (Dehaene & Cohen, 1995) and neuroimaging research (Dehaene, Piazza, Pinel, & Cohen, 2003). The processing of verbal numerals is implemented by perisylvian regions of the left hemisphere, most notably the region around the angular gyrus. Processing of Arabic numerals is postulated to depend bilaterally on the region of the fusiform gyrus, the areventrolateral border. Bilaterally situated neuronal networks around the horizontal portion of the intraparietal sulcus may constitute the neuronal substrate the ANS (Walsh, 2003). Strategic aspects of number processing depend on the dorsomedial and dorsolateral regions of the prefrontal cortex and related circuits. Proceduralization of arithmetic operations takes place via interactions between circuits comprising the before mentioned regions and subcortical basal ganglia structures, resulting in a specific domain of semantic memory, the arithmetical facts, represented in widely distributed form in several cortical areas, but having the angular gyrus as a kind of hub or portal of access (Zamarian, Ischebeck, & Delazer, 2009).

NUMBER TRANSCODING

The mastery of reading and writing numbers in different notational systems is an essential skill in current days. Daily activities require the communication of numerical information, such as registering a telephone number or performing calculations. The ability to establish a one-to-one correspondence between any number presented in one notational system and its counterpart another system is called number transcoding (Deloche & Willmes, 2000).

Since the beginning of the 1980's, when the first cognitive models for numerical cognition were proposed, number transcoding has been a recurrent topic of investigation. Here a review of the literature on number transcoding abilities will be presented, focusing on the assumptions underlying the most accepted cognitive models as well as their inherent limitations. We will also discuss practical and theoretical implications of number transcoding in the context of mathematics learning difficulties.

An overview on the cognitive models of number transcoding

The first systematic investigations on number transcoding date back to the beginning of the 1980's, developed by the neuropsychologists Gérard Deloche and Xavier Seron (Deloche & Seron 1982a; Deloche & Seron 1982b; Seron & Deloche, 1983; Seron & Deloche, 1984). In four classical works they conducted a series of case studies on aphasic patients, highlighting their performance in converting between Arabic and verbal numerals. Based on the selective deficits presented by the patients, the authors argued in favour of a relative independence of the language and number domains.

The independence of cognitive mechanisms within the number domain was also proposed in these publications. A key reporting was the dissociation between numerical lexical and syntactic mechanisms according to the erroneous responses observed in aphasic patients. Errors could be attributed to a lexical mechanism, when a lexical element in the number was replaced by another one, for example, when 45 was transcoded as 46, or when 12 was transcoded as 20. Errors in the syntactic mechanisms, which were the vast majority of transcoding errors, occurred when the lexical elements were misplaced in the syntactic frame, or when this frame was wrongly generated, for example, when 150 was transcoded as 1050. This sort of errors were then explained as the use of inappropriate strategies in converting the syntactic structure of the numerical input and output (Deloche & Seron, 1982a, 1982b). These were the starting point for the elaboration of number transcoding as an algorithm-based process.

Later on, different transcoding models were developed based on a wide range of evidences, such as case studies in adult patients (McCloskey et al., 1985), cognitive development (Power & Dal Martello, 1990; Seron & Fayol, 1994), and computational simulations (Barrouillet, Camos, Perruchet, & Seron, 2004; Verguts & Fias, 2006). Importantly, the basic disagreement between the models lies in the role attributed to number semantics and procedural algorithms in the transcoding process, so that they can be grouped in two main categories: semantic and asemantic models. These models will be described in more detail in the next sections.

Semantic models

A number transcoding model can be derived from the broader model of numerical cognition of McCloskey, Caramazza and Basili (1985) and McCloskey (1992). According to this model of numerical processing, there are two independent mechanisms of numerical comprehension, one specific to Arabic inputs, and the other to verbal inputs. Likewise, two mechanisms of Arabic and verbal production are responsible to these specific outputs. An additional calculation module takes part in all numerical operations, regardless of the input notation. Evidences were taken from cases of double dissociation involving the comprehension/production mechanisms, Arabic/verbal notations, and the lexical/syntactic processing.

The central aspect of this model is the presence of an internal semantic representation that mediates all the possible paths between input, output and calculation mechanisms. In this semantic module, all the inputs (regardless of its notation) are decomposed into an abstract representation that designates number's meaning through their associated base-ten structure, similar to a place-value notation. For example, in the McCloskey model (1992), the semantic representation of the number 743 is equivalent to $[7]10^2 + [4]10^1 + 3[10]^0$, so that the values of the digits 7, 4 and 3 are assigned to the hundreds, tens and units, respectively. Finally, transcoding procedures of the verbal or Arabic production mechanisms act on this semantic representation, depending on the demanded output notation.

Power & Dal Martello (1990) later proposed a similar model, assuming that the semantic representation is constructed based on linguistics aspects of the lexical and syntactic organization in the number word system. For example, the semantic representation of 365 is built as (C3 X C100) + ([C10 X C6] + C5). After this representation is built, two different operations take place. The first is the overwriting (#), which reflects the sum relations in the Arabic code: ([C10 X C6] + C5) = 60 # 5 = 65. This component is observed, for example, when one incorrectly writes 1000400503 instead of 1453, reflecting a full literal transcoding the lexical units from the verbal code (1000 + 400 + 50 + 3). The second is the concatenation (&), which reflects multiplication relations: (C3 X C100) = 3 & 100 = 300. Interestingly, the authors assume that the model can explain erroneous transcoding by both semantic and asemantic perspectives, as the transcoding rules that take part in the comprehension and production mechanisms are well described (Power & Dal Martello, 1997). The lexical-semantic model of Power and Dal Martello is considered the most influential semantic model, and was used for interpretation of erroneous transcoding in normal children (Power & Dal Martello, 1990, 1997; Seron & Fayol, 1994) and in neuropsychological cases (Cipolotti, Butterworth, & Warrington, 1994).

The semantic models presented important problems and, therefore, were hardly criticized. Firstly, semantic models were built mainly by studying double dissociations. Nevertheless, similar studies using the same method did not support the hypothesis of unitary mechanisms for calculations (Deloche & Willmes, 2000). Secondly, it has been claimed, and consistently shown by empirical data, that number transcoding is better explained by a solely asemantic route (discussed in deeper detail below in this text). Finally, dissociations reported in single patients is subjected to several statistical caveats and, therefore, should not be used as the unique source of evidence (Deloche & Willmes, 2000).

Asemantic models

Asemantic models assume that the number transcoding is a procedure in which the numerical meaning (that is, its semantics) is not encoded. Two kinds of asemantic models have been developed: algorithm-based production systems and connectionist neural networks.

Algorithm-based models were first proposed by Deloche, & Seron (1987), with evidence from case studies. According to these models, the numerical output is generated after lexical and syntactic rules operate directly on the input string, with no need of an intermediate level of semantic coding. More recently, Barrouillet et al (2004) proposed an asemantic developmental model of number transcoding from the oral verbal to Arabic format, called A Developmental, Asemantic, and Procedural Transcoding (ADAPT) model, which explains transcoding performance through the acquisition of conversion rules. In the first step of the model, the verbal input is temporarily stored in the phonological buffer. Afterward, if this content in working memory matches the lexical units stored in long-term memory, then the digital form can be directly retrieved. When this is not possible, a parsing process divides this content into units that can be processed. At this, a set of procedural rules operate by reading the content of working memory and entering new representations or filling out representations, in such a way that a syntactic frame is created and filled in with the digital forms. The triggering of transcoding procedures is conditioned by the representations present in working memory. Table 1 shows an example of the functioning of ADAPT procedures.

Table 1
Example of ADAPT^{ADV} Functioning

Step	Enter	Procedure	Chain	WMS	Frame
		Dois mil oitocentos e três (2803)			
1	Dois	P1		2	No
2	Mil	P3b	2 _ _ _	No	Yes
3	Oito	P1	2 _ _ _	8	Yes
4	Centos	P2d	2 8 _ _	No	Yes
5	Três	P1	2 8 _ _	3	Yes
6	END	P4c	2 8 _ 3	No	Yes
7	END	P4b	2 8 0 3 stop	No	No

Note. WMS = Working memory store.
Adapted from "ADAPT: A developmental, asemantic, and procedural model for transcoding from verbal to Arabic numerals", by Barrouillet et al., 2004, Psychological Review, 111(2), 368-394.

ADAPT accounts for the development of number transcoding by means of an expansion of the numerical lexicon (i.e., the stock of new units in long-term memory via experience: single-digit numbers, teens, decade numbers, and all two-digit numbers later during development) and improvement of the conversion rules.

The ADAPT model can be considered a classical model of information processing and, as such, it can be more easily operationalized in terms of cognitive-neuropsychological constructs. A growing body of neuropsychological literature is based on the ADAPT model (Camos, 2008; Pixner et al. 2011a; Pixner, Moeller, Hermanovà, Nuerk, & Kaufmann, 2011b; Zuber, Pixner, Moeller, & Nuerk, 2009).

Dual-route models

There were also some models considering both semantic and asemantic transcoding routes, aiming at conciliate new empirical findings (mainly from case studies) and the previous models (Cipolotti, 1995; Cipolotti & Butterworth, 1995; Cohen, Dehaene, & Verstichel, 1994). Cipolotti and Butterworth (1995) described a neurological patient who showed a striking performance pattern in numerical tasks, which could not be accommodated by the number processing models available at that time. The patient could identify and perform calculations on Arabic numerals and written number words, but could not write or read them aloud, thus suggesting that number transcoding could also demand an asemantic pathway. The authors added three asemantic routes to the model of McCloskey, Caramazza and Bazili (1985). These routes were then responsible for the transcoding between Arabic and verbal, verbal and verbal written and oral modalities, and could be activated depending on specific task demands.

Similarly, Cohen, Dehaene and Verstichel (1994) reported a patient presenting deep dyslexia, which also affected the processing of Arabic numerals. The patient showed impaired abilities in reading aloud unfamiliar numerals, but was able to read aloud familiar numerals of matched complexity, and to understand the semantic content of a number. Interestingly, the patient committed some semantic errors with familiar words and numerals. For example, some important dates were mixed up, such as 1918, reported by him as the end of the World War I, was read as “1940”. This pattern is incompatible with one-route models of number transcoding, so that the authors proposed the existence of a “surface” route, in which language-specific rules are applied to the digit string, and a “deep” semantic route, that works only for familiar numerals with strong lexical/semantic entries. In this route, the semantic representation of the numerical input allows the retrieval of the adequate lexical entry. Importantly, only familiar numbers, which the authors refer to as “label” numbers or numbers with “encyclopedic” meaning (such as important dates, brands of cars, etc.) can be represented by this semantic route.

Connectionist model of Arabic number reading

Rule-based approaches for number transcoding may be criticized on at least two grounds. Firstly, production systems, such as the ADAPT model (Barrouillet et al., 2004) assume that rules originate from declarative knowledge, being explicitly taught. However, the sort of declarative knowledge, the way it is acquired, and the mechanisms by which it is transformed into rules are not specified. Secondly, assumption of all-or-nothing rules is not compatible with some evidences, such as the inconsistency in the application of the same rule by subjects. For example, the patient HY (McCloskey, Sokol, & Goodman, 1986), committed an error in the retrieval of a number within a lexical class, namely, writing 5 when hearing “seven”. Nevertheless, this same error did not appear every time he heard the lexical input “seven”, contrary to what was expected in an all-or-nothing scenario.

A neural network model simulating reading of Arabic numerals from 1 up to 999 was developed by Verguts and Fias (2006), simulating transcoding by means of learning algorithms based on the individual frequency of numbers. The model was composed of three layers, an Arabic input layer, a hidden layer and a phonological output layer. Direct forward links connected the input and the output layers. The hidden layer indirectly connected the input and output layers in parallel to the direct connections. The hidden layer received three kinds of connections: a) forward connections from the input layer, b) bidirectional connections with the output layer, and c) recurrent connection of the hidden layer itself. Recurrent connections allowed the hidden layer to function as a kind of contextual layer. At each computing step, a contextual layer is able to feed the system with the state of activation corresponding to the immediately previous step (Elman, 1990). In this way, the contextual layer emulates a working memory device, allowing the implementation of sequences of activation. Contextual layers with recurrent connections constitute an important computational device in the connectionist modelling of seemingly rule-based behavior (Dominey, 1997).

The simulation studies by Verguts and Fias (2006) demonstrate that connectionist models are a viable and elegant architecture to implement transcoding processes. However, lack of explicit differentiation between architecture, representations and processes is both an asset and a weakness. On the one hand, connectionist models suggest how complex cognitive processes emerge from the dynamics of self-organizing systems. On the other hand, connectionist models are difficult to operationalize in the neuropsychological research with patients. Predictions derived from production systems are easier to operationalize and interpret in neuropsychological terms. For example, the ADAPT model (Barrouillet et al., 2004) predicts that transcoding performance depends both on working memory and phonemic awareness, two traditional neuropsychological constructs.

What sort of semantic activation?

A central aspect of the cognitive models that argue in favor of a semantic route for number transcoding still deserves more attention. Up to now, there is no consensus on the nature of this semantic representations. The McCloskey's model (1992) and the lexical-semantic model of Power and Dal Martello (1990, 1997) defined a semantic route with a place-value and base-ten structure, which refers to the numerical quantity (numerosity) of numerals.

Moreover, it is important to note that these models defined numerical semantics appealing to artificial symbolic notations, for example, the Indu-Arabic system.

The dual-route model of Cohen, Dehaene and Verstichel (1994) designates a semantic route with a different nature. In this model, the way by which a number is conveyed by the semantic route, during number transcoding, has no connection to its numerosity but with its encyclopedic meaning. In fact, they proposed the semantic content of a number by lexical entries stored in the long-term memory (semantic memory).

After the publication of the ADAPT model, semantic and dual-route models of number transcoding have been left aside. Since then, only a few studies have been resorting to semantic routes to interpret their data and, in some cases, the definition of its nature differs from what was defined by semantic and dual-route models. Van Loosbroek, Dirkx, Hulstijn and Janssen (2009) investigated number writing abilities in children and found that children with poor arithmetical abilities rely on a semantic route to transcode small (up to 9) and large numbers (up to 99), while children with normal arithmetical abilities only use the semantic route for larger numbers. This interpretation was made based on the observed magnitude effect: children were faster when writing smaller numbers than larger ones. Similarly, Imbo, Bulcke, Brauwer and Fias (2014) also reported a magnitude effect on error rates of children with less transcoding skills. In both studies, the presence of the magnitude effect indicates that, in number transcoding, numerical magnitudes are retrieved from the mental number line and, due to its logarithmic compression, larger magnitudes are harder to recover (Ansari, 2008).Therefore, the nature of the semantic route in number transcoding would lie in the mental number line, that is, in an analogue representation of numerical magnitudes which follows the Weber-Fechner psychophysical law.

The problem with this assumption is that it does not take into account the frequency with which the numbers occur in the language. As previously shown by Dehaene and Mehler (1992), smaller numbers, and some larger round numbers, tend to occur more often.

Because of it, their output form can be directly retrieved from the lexicon, bypassing any additional stage of algorithm application or semantic access (Barrouillet et al, 2004). Therefore, the magnitude effect observed in number transcoding could be a simple reflex of differences in number frequencies.

Number transcoding and general cognitive abilities

Working memory

Working memory (WM) plays an important role on many aspects of numerical cognition (Geary, 2011). Concerning number transcoding, the only model that has clear assumptions about WM operation is ADAPT. According to the ADAPT model, after the phonological input is segmented by the parsing process, it is stored in a phonological buffer and then it is analyzed by the WM. When the contents of WM match the conditions for the application of a given procedure, this procedure is triggered. The contents in the WM consists of declarative knowledge in different forms: a) units isolated by the parser; b) lexical elements retrieved from long-term memory and; c) new representations constructed by the procedures already applied. After the application of the procedures, WM representations consist of an ordered sequence of digits or blank spaces (frames) that will be filled in subsequent stages. Therefore, WM is involved in the crucial stages of rule application, long-term memory access, and in the output construction.

These assumptions have been consistently endorsed by empirical evidences. Studying number transcoding in 7-year-old children with different profiles of verbal working memory, Camos (2008) found a robust association of transcoding complexity (measured by the quantity of conversion rules defined by the ADAPT model). Furthermore, individual differences in the transcoding performance were well explained by differences in working memory capacities. A specific role for visuospatial and central executive working memory processing in number transcoding could be inferred in a study by Zuber et al. (2009) with typically developing German-speaking children. As it is well known, German language requires an inversion between units and decades, which is a hindrance to learning verbal numerals and Arabic-verbal transcoding, and determines more than 50% of errors committed by 7 year-older children. The impact of a less transparent number-word system (i.e., inverted) was further explored by Pixner and collaborators (2011a, 2011b) in 7-year-old Czech-speaking children. The Czech language provides a unique opportunity to disentangle the impact of the verbal system on numerical processing, as there exist two different number-word systems, and one of them is inverted. In his work, Pixner et al. (2011a, 2011b) found higher frequencies of inversion-related errors when children had to transcoding numbers presented in the inverted notational system, thus accompanied by higher demands on working memory resources.

Phonemic awareness

Phonemic awareness is a subcomponent of phonological processing which is related to the ability to perceive and manipulate phonemes that constitute words (Wagner & Torgesen, 1987). It has been constantly related to reading and writing performance and disabilities (Vellutino, Fletcher, Snowling, & Scanlon, 2004) and recent studies also suggest that it might be related to arithmetic performance and number processing (Simmons & Singleton, 2008). Regarding number transcoding, specifically Arabic number writing, the input is verbal, hence one must be able to differentiate between sounds of language to correctly comprehend the verbal number that will be transcoded into the Arabic form. Despite this possible impact of phonological skills in the transcoding performance, no study has simultaneously and systematically investigated the relationship between these two variables.

Studies on children with reading difficulties also suggest that number transcoding might be influenced by verbal mechanisms. Recently, Moll, Göbel, & Snowling (2014) investigated the neuropsychological profile of 6 to 12-year-old children with difficulties only in mathematics (MD), in both mathematics and reading (MD+RD) , only in reading (RD) and control groups. The RD group did not present deficits in the nonsymbolic aspects of mathematics, yet were particularly low on verbal tasks, especially number transcoding. This finding suggests that children with reading difficulties, who presumably present deficits in phonological processing, struggle in numerical tasks that involve the verbal code, regardless of their unimpaired approximate number system.

Development of number transcoding abilities

The study of number transcoding is especially important in young children at the beginning of school life, since it allows the investigation of the steps through which the basic transcoding principles are acquired by analyzing the errors they commit. In fact, many evidences suggest that the comprehension of the place-value syntax of Arabic numbers, and how to match it with the spoken number words, constitutes one of the main challenges imposed to young children (Geary, 2000), and requires about three years of formal education to be fully acquired (Nöel & Turconi, 1999), despite no study has investigated it in detail.

Because the verbal and Arabic codes have different structures, preventing a direct conversion from one code to the other, number transcoding is one of the first numerical skills that needs to be formally taught. Transcoding imposes some difficulties especially for children in early schooling, who are not completely familiar with the syntax of the Arabic notation, as evidenced by the predominance of syntactic errors over lexical ones in children (Camos, 2008; Power & Dal Martello, 1990; Seron, Deloche, & Noël, 1992; Seron & Fayol, 1994; Zuber et al., 2009). Nevertheless, children seems to acquire rudimentary knowledge of the place-value syntax even long before they join school lectures (Barrouillet, Thevenot, & Fayol, 2010), probably due to implicit learning in daily life (Byrge, Smith, & Mix, 2014).

The structure of the number word system may also impose further difficulties for the learning of number transcoding in young children. When the order of base numbers in the verbal system is not consistent with the Arabic notation, that is, higher-before-lower ordered, the relation between the verbal and the Arabic codes is not fully transparent. An inversion in the order of the bases 10^1 and 10^2 in the number word system is a basic feature of in many languages, such as Danish, Arabic, German, Dutch and partly in Czech (which possess both a inverted and a non-inverted system). In these less transparent number word systems, children demand some extra time to master number transcoding (Pixner et al., 2011a, 2011b; Zuber et al., 2009). As shown by Zuber and colleagues (2009), the higher difficulty in transcoding numbers in languages with this inversion property rests on the extra demand on children's working memory resources.

Power and Dal Martello (1990), analyzed the performance of normally developing children in the beginning of the second grade (around 7 years-old) in an Arabic number writing task. They found that children at this age were able to write 2-digit numbers flawlessly, but showed problems when writing 3- and 4-digit numbers. Most of the errors were due to difficulties in transcoding the more complex numbers (with internal zeros). Error analysis revealed that more than 85% of incorrect responses were due to mistakes on number syntax. In a second study (Power & Dal Martello, 1997), using an Arabic number reading task, the most frequent reported error was also syntactic, due to the subdivision of the string sequence in smaller units (for example: 365 read as three - six - five).

Using a longitudinal design, Seron, Deloche and Nöel (1992) evaluated transcoding abilities (both Arabic number reading and writing) three times in a year in Belgian children (French speaking). They found a performance improvement from the second to the third measuring times, with an overall better performance on the number reading task. Second graders also had a benefit from schooling, once they showed an improvement in performance from the beginning to the end of the year. On the other hand, this was not the case for third graders, as they showed a low improvement on their mean scores due to a ceiling effect from the middle of the school year ahead. Similar results were also found by two other studies. Sullivan, Macaruso and Sokol (1996) tested children from third, fourth and seventh school grades. None of the children exhibit major problems with 3- and 4-digit numbers, as their correct answers rate was always high, and the larger majority of wrong responses (above 90%) were classified as syntactic.

Finally, when investigating the performance of French second graders, Camos (2008) also found that these children could perfectly write Arabic numbers up to 100, and committed fewer errors in the 3-digit numbers (22.4%) in comparison to the 4-digit numbers (47.2%).

Number transcoding and mathematics achievement

Besides the close relation between number transcoding and mathematics achievement, there is only relatively few studies investigating transcoding abilities in children with math learning difficulties.

Children with developmental mathematics learning disorders (MD) are currently defined in the medical nosology as persistent and severe difficulties in acquiring specific abilities related to math, which cannot be ascribed to secondary factors such as emotional and educational inadequacies, lack of general intelligence or sensorimotor impairments (Butterworth, 2005). They have trouble in acquiring several number processes and calculation abilities, including simple calculations and memorizing arithmetic facts (Butterworth, 2005; Mazzocco, 2007; Gross-Tsur, Manor, & Shalev, 1996) as well as other abilities concerning magnitudes perception and the comprehension and use of symbolic codes to represent numerical information (Roussele & Noël, 2007; Dehaene, 1992; Wilson & Dehaene, 2007).

Evidences suggests that number transcoding may impose difficulties for younger children with mathematics difficulties, while for older ones this difficulty seems to be overcome (Geary, Hoard, & Hamson, 1999; Geary, Hamson, & Hoard, 2000). Nevertheless, there is still no conclusion about the magnitude of this difficulty, and when it stops being a problem for these children.

Moreover, evidences are still not conclusive regarding the nature of the poor transcoding performance in children with mathematics difficulties. Until today, only one study assessed this issue in detail. In the study mentioned above, Van Loosbroek et al., (2009) used an electronic device to capture reaction times in an Arabic number-writing task. They found no group differences in the error rates but in the reaction times, and argued that children with mathematics difficulties would use a less efficient, semantic rooted, for transcoding numbers. Nevertheless, a more detailed analysis of the errors committed by these children would allow a deeper analysis of the transcoding processes that could be impaired (lexicon, syntactic, etc.).

CONCLUDING REMARKS

In summary, the studies reviewed above confirms the importance of the symbolic systems in the study of numerical cognition. In this context, number transcoding abilities are of main interest, as taps on both verbal and Arabic representations of number, and is well described by cognitive models.

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CHAPTER 2

NUMBER TRANSCODING IN CHILDREN.

STUDY 1: FROM "FIVE" TO 5 FOR 5 MINUTES: ARABIC NUMBER TRANSCODING AS A SHORT, SPECIFIC, AND SENSITIVE SCREENING TOOL FOR MATHEMATICS LEARNING DIFFICULTIES.

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Abstract

Number transcoding (e.g., writing 29 when hearing "twenty-nine") is one of the most basic numerical abilities required in daily life and is paramount for the achievement in more complex numerical activities. The aim of the current study is to investigate psychometric properties of an Arabic number-writing task and its capacity to identify children with mathematics difficulties. We assessed 786 children (55% girls), with a mean age of 9y5m, who were further classified as children with mathematics difficulties (n = 103) or controls (n = 683). Although error rates were relatively low, the task presented adequate internal consistency values (kr20 = 0.91). ROC analyses revealed effective diagnostic accuracy in 1st and 2nd school grades (specificity equals to 0.67 and 0.76 respectively, and sensitivity equals to 0.70 and 0.88 respectively). In addition, items measuring the understanding of place-value syntax were the most sensitive to mathematics achievement. Given the current results, we propose that number transcoding tasks are a useful tool for the assessment of mathematics abilities in early elementary school.

INTRODUCTION

Daily activities require the communication of numerical information, such as registering a telephone number or making mental calculations. Besides that, being able to manipulate numbers is one of the first steps in mathematical learning, which begins to be formally trained in kindergarten. Learning the Arabic notation is one of the main challenges faced by young children in the first years of school, especially because of its place-value syntax (Geary, 2000). A useful tool for investigating children's knowledge of numerical syntax is the number transcoding task. This task requires the conversion of numerical symbols between verbal and Arabic numerical notations (Deloche & Seron, 1987).

The verbal number system is composed by a lexicon that designates some numbers (e.g. *five*, *eleven*), the bases by which they are multiplied (e.g., "ty" in *seventy*; *hundred*), as well as by a syntax that organizes these lexical units to represent any possible quantity. In turn, the Arabic number system possesses a lexicon of only ten elements. Its basic syntactic principle is the place-value, according to which the actual value of a digit is given by its position in the number.

The ADAPT model (A Developmental, Asemantic and Procedural Transcoding) by Barrouillet, Camos, Perruchet, and Seron (2004) accounts for this conversion from the verbal-oral to the Arabic form by means of representing information in phonological short-term memory, and by the lexical retrieval and rule application, which are driven by condition-action rules. When the lexical units in the verbal input match a Arabic form stored in long-term memory (e.g. *one* -> 1, *fifteen* -> 15), then the output is directly retrieved. Otherwise, specific rules are triggered, and operate recursively in the verbal string present in the input in order to build the correct output in the Arabic notation. The conditions that trigger a given rule can be either the class of the lexical primitives (unit, decade, hundreds, for example) or the presence of empty slots. There are eight different procedures triggered by the rules, such as "finding the positional value of the lexical primitive" (how many slots the frame must have), "filling empty slot with 0", among others. These rules are devoted to (i) the retrieval of information from long-term memory (LTM) (called P1 rules, responsible for retrieving "3" from its verbal form), (ii) to manage the size of digital chains (P2 and P3 rules; in "2003", these rules create a frame of four slots) and (iii) to fill these slots (if there are any empty slots, P4 rules will fill them with 0s).

Concerning the development of number transcoding in children, evidence suggests that the acquisition of the numerical lexicon (Wynn, 1992) and basic principles of numerical syntax (Barrouillet, Thevenot, & Fayol, 2010) are already acquired even before elementary school. During the first school years, the development of number transcoding skills is highly influenced by numerical length (quantity of digits) and syntactic complexity (quantity of transcoding rules). By the beginning of the second grade children already master the writing and reading of 2-digit numbers, showing major difficulties in the transcoding of 3- and 4-digit numbers (Camos, 2008; Moura et al., 2013; Power & Dal Martello, 1990, 1997; Seron, Deloche, & Noël, 1992). Most of these difficulties is due to the place-value syntax of these larger numbers. In third and fourth graders, difficulties in number transcoding are scarce, and concentrated in 3- and 4-digit numbers with a more complex syntactic structure, such as the ones containing internal zeros (Moura et al., 2013; Sullivan, Macaruso, & Sokol, 1996). Therefore, numerical transcoding abilities for numbers up to four digits appear to be fully achieved in typically developing children after three years of formal education (Nöel & Turconi, 1999).

Only few studies have investigated the association between number transcoding and arithmetic achievement in school children. Examining first graders, Geary, Hoard, and Hamson (1999) and Geary, Hamson, and Hoard (2000) found a significant association between reading and writing of small numbers and formal mathematics achievement. Using a longitudinal approach, Moeller, Pixner, Zuber, Kaufmann, and Nuerk (2011) showed that, compared to working memory capacity and non-symbolic representations of numbers, the knowledge of place-value syntax in the end of first grade is the best predictor of mathematics achievement two years later. Furthermore, syntactic errors in an Arabic number writing task and the decade-unit compatibility effect in a two-digit number comparison task (Nuerk, Weger, & Willmes, 2001) have proved to be particularly important to characterize and predict mathematics achievement in children (Moeller et al., 2011).

Difficulties in number transcoding have also been observed in children with developmental dyscalculia or mathematics learning difficulties. Studies suggests that writing and reading Arabic numbers impose relevant obstacles to younger children with mathematics learning difficulties aging around 7-years-old (Geary, Hoard, & Hamson, 1999; Geary, Hamson, & Hoard, 2000). In turn, in older children (8- and 9-years-old) these difficulties in number transcoding seem to be already overcome (Landerl, Bevan, & Butterworth, 2004). This issue was investigated in deeper detail by Moura et al. (2013), using more complex transcoding tasks containing numbers with up to 4 digits, and with increasing syntactic complexity. Results revealed significant differences between children with mathematics difficulties and typical achievers, from the first to the fourth grades, in both Arabic number reading and writing, but with effect-sizes decreasing with grade. Importantly, in middle elementary grades, children with mathematics difficulties showed higher error rates in numbers with higher syntactic complexity. Moreover, an analysis of the erroneous responses suggested that, in early elementary school, children with mathematics difficulties struggle with both place-value syntax of Arabic numbers and with the acquisition of a numerical lexicon. In middle elementary school, the difficulties observed in children with mathematics difficulties were specific to the syntactic composition of Arabic numbers. The authors thus argued that, after the first school grades, children with mathematics difficulties are able to compensate at least part of their number transcoding deficits.

In summary, the literature on number processing and mathematics difficulties indicates that transcoding tasks are sensitive to and have a good predictive validity for mathematics difficulties (Moeller et al., 2011; Moura et al., 2013). Moreover, its cognitive underpinnings have been well characterized by current information processing models (Barrouillet et al., 2004; Camos, 2008; Cipolotti & Butterworth, 1995). Nevertheless, the diagnostic properties of number transcoding remain largely unexplored. In view of the above, one may consider the usefulness of number transcoding tasks in the screening of mathematics difficulties.

To our knowledge, there is no standardized task for assessing number transcoding abilities in school children. Even though number transcoding tasks are largely used in the investigation of numerical abilities in children (Geary, Hoard, & Hamson, 1999; Geary, Hamson, & Hoard, 2000; Landerl, Bevan, & Butterworth, 2004; Moura et al., 2013) and adults suffering from neurological impairments (Deloche & Seron, 1982a, 1982b; Seron & Deloche 1983, 1984), there are no reports on reliability, validity and item properties of such tasks. In general, studies using number transcoding tasks are conducted in the context of pure experimental neuropsychology, in which psychometric properties are presumed and never explicitly investigated.

The aim of this study is to determine reference values and psychometric properties of a verbal to Arabic transcoding task in Brazilian school-aged children. In the present study, we assessed number transcoding by means of a number dictation task, in which numbers are orally presented and the child should write them in their Arabic form. The task was previously designed in the context of a wider investigation of mathematical abilities in children (Haase, Júlio-Costa, Lopes-Silva, Starling-Alves, Antunes, Pinheiro-Chagas, & Wood, 2014; Lopes-Silva, Moura, Júlio-Costa, Haase, & Wood, 2014; Moura et al, 2013). We reported normative parameters such as mean, range values and percentiles for 1st to 4th grades obtained from a large sample of school children. In addition, the diagnostic accuracy of the number writing task in the detection of children at risk for mathematical difficulties, as well as the influence of place-value syntax in children's achievement, were investigated.

METHODS

Participants:

The sample was constituted by children attending to first to fourth grades in both public and private schools in the Brazilian cities of Belo Horizonte and Mariana. Data collection took place in 10 schools in Belo Horizonte (7 public), and 2 schools in Mariana (1 public). In Brazil, public schools are mostly attended to by children of lower to middle socioeconomic status. All study procedures were approved by the local university ethics committee.

In total, 985 children (85% from public schools) were assessed using the following three tasks: Arithmetics and Single-word spelling subtests of the Brazilian School Achievement Test (Teste do Desempenho Escolar, TDE, Stein, 1994), and the Arabic Number-Writing Task. Testing was conducted in classrooms of 10 to 20 pupils. Children with mathematics difficulties were those with performance below the 25th percentile in the Arithmetics subtest and the performance above the 25th percentile in the spelling subtest. Children with performance above the 25th percentile in both TDE subtests were classified as controls.

Instruments

Number transcoding task

Arabic Number-Writing Task: Children were instructed to write down the Arabic numerals that corresponded to the dictated numbers (one-hundred-and-fifty → “150”). The task was composed by 28 items with 1- to 4-digit numbers. The use of three- and four-digit numbers intended to avoid numbers with strong lexical entries. The three- and four-digit numbers were grouped into three categories according to their complexity level (low, moderate and high complexity numbers), which were defined based exclusively on the number of algorithmic transcoding rules necessary to transcode each individual item. This criterion was based upon the ADAPT model, which relates item complexity to the number of algorithmic rules necessary to transcode a number (Barrouillet et al., 2004): the more transcoding steps must be performed, the more difficult is an individual item. The administration of the Arabic Number-writing Task lasted for about five minutes in individual assessments, while in collective assessments this duration increased to about 10 to 15 minutes. One point was assigned to each correct written number. There was no interruption criteria and no time limits, and one point was attributed to each correct answer.

Table 1
The 28 items of Arabic Number-writing Task according to complexity level.

Item	Number	Complexity	Rules (ADAPT)	Error Rate	Item-total Correlation
1	4	null	2	0.000	-
2	7	null	2	0.000	-
3	1	null	2	0.003	.076
4	11	null	2	0.003	.101
5	40	null	2	0.010	.240
6	16	null	3	0.003	.051
7	30	null	2	0.005	.253
8	73	null	3	0.034	.367
9	13	null	2	0.006	.047
10	68	null	3	0.031	.332
11	80	null	2	0.005	.266
12	25	null	3	0.000	-
13	200	low	3	0.033	.543
14	109	moderate	4	0.046	.619
15	150	low	3	0.059	.717
16	101	moderate	4	0.045	.630
17	700	low	3	0.057	.590
18	643	high	5	0.093	.755
19	8000	low	3	0.107	.632
20	190	low	3	0.080	.714
21	1002	moderate	4	0.182	.665
22	951	high	5	0.111	.747
23	1015	moderate	4	0.207	.804
24	2609	high	7	0.271	.806
25	1300	moderate	4	0.221	.851
26	3791	high	7	0.276	.788
27	1060	moderate	4	0.261	.780
28	4701	high	7	0.266	.810

General school achievement

School Achievement Test: The Teste de Desempenho Escolar (TDE; Stein, 1994) is the most widely used standardized test of school achievement in Brazil. The TDE comprises three subtests tapping basic educational skills: single-word reading (which was not used in the present study), single-word spelling to dictation and basic arithmetic operations. The word spelling subtest consists of 34 dictated words with increasing complexity. The examiner dictated a word and afterwards a sentence containing this word, and finally repeated the word once more. One point was assigned to each correctly written word. The arithmetic subtest is composed of 3 simple oral word problems that require written responses (e.g. “John had nine stickers. He lost three. How many stickers does he have now?”) and 45 basic arithmetic calculations of increasing complexity that are presented and answered in writing (e.g. “1+1=?” and “(-4) x (-8)=?”. One point was assigned to each correct calculation. Reliability coefficients (Cronbach's α) are around 0.8 or higher. Children are instructed to work as much as they can, without time limits.

RESULTS

The Arabic Number-Writing Task did not impose major difficulties to the children. Overall, 55% of all children completed the task faultlessly. When analyzing each group separately, 57% of control children and 36% of children with mathematics difficulties did not commit any errors. There was a clear developmental trend in the task performance, as the rate of correct items increased along with grade (Table 2, Figure 1). As percentile distributions in Table 2 suggests, the task showed a ceiling effect for all children in the third and fourth grades.

Reliability and internal consistency of the Arabic Number-Writing Task

Internal consistency was assessed by means of the KR-20 formula, which estimated a value of 0.91, indicating a high internal consistency. Table 2 presents KR-20 values separately for each grade, indicating high indexes up to the 2nd grade. The high internal consistency was further confirmed by a split-half analysis of the whole sample (r = 0.94).

Table 2

Mean scores, internal consistency and percentile ranks in Arabic Number-writing Task according to school grade and group.

	Mean Number transcoding scores											
	1st grade			**2nd grade**			**3rd grade**			**4th grade**		
Control children	16.80 (3.22)			24.63 (3.11)			27.60 (.67)			27.85 (.36)		
Children with MD	12.80 (3.33)			15.92 (3.12)			26.50 (1.66)			27.34 (1.15)		
Reliability (KR-20)	.79			.88			.46			.33		
Cummulative percent												
Total score	**Overall (n=55)**	**Control (n=45)**	**MD (n=10)**	**Overall (n=249)**	**Control (n=224)**	**MD (n=25)**	**Overall (n=225)**	**Control (n=189)**	**MD (n=36)**	**Overall (n=257)**	**Control (n=225)**	**MD (n=32)**
8	2		10									
9	4		20									
10	5		30									
11	7		40									
12	15	9	50	1								
13	24	18	70	3		12						
14	40	33	90	4		32						
15	53	44	100	5		40						
16	55	47		6		52						
17	64	58		7		60						
18	67	62		8		72						
19	76	71		12	5	76						
20	87	84		21	14	88						
21	95	94		31	23	100						
22	100	100		37	30							
23				45	39		2		11			
24				51	46		2		14			
25				58	53		4		25	2		16
26				62	58		15	11	36	3		22
27				73	70		35	29	64	17	15	28
28				100	100		100	100	100	100	100	100

Note. numbers in brackets represents standard deviations.

MD = mathematics difficulties.

Item analysis

Error rates for individual items varied from 0 to 28%, being particularly small for one- and two-digit numbers. Among one- and two-digit numbers, the most difficult one presented an error rate of modest 3%. Table 1 depicts error rates for each item, and Figure 1 depicts error rates separately by grade and children's group. Two-digit numbers only imposed noticeable difficulties for 1st graders with mathematics difficulties. Among 3- and 4-digit numbers, higher error rates were observed in control children attending the 1st grade only, and children with mathematics difficulties attending 1st and 2nd grades. Third graders with mathematics difficulties still showed some difficulties in transcoding the more syntactically complex numbers. In 4th grade, both groups showed similar and almost flawless performance.

For the analyses of the item discriminability, item-total correlations were calculated (Table 1). One-and two-digit numbers showed low discriminability indexes (i.e. < 0.40), which are in line with the very low error rates presented by these items. In turn, three-and four-digit numbers showed higher discriminability, varying from 0.54 to 0.85, thus suggesting that numbers with higher syntactical complexity are more discriminative for testing purposes.

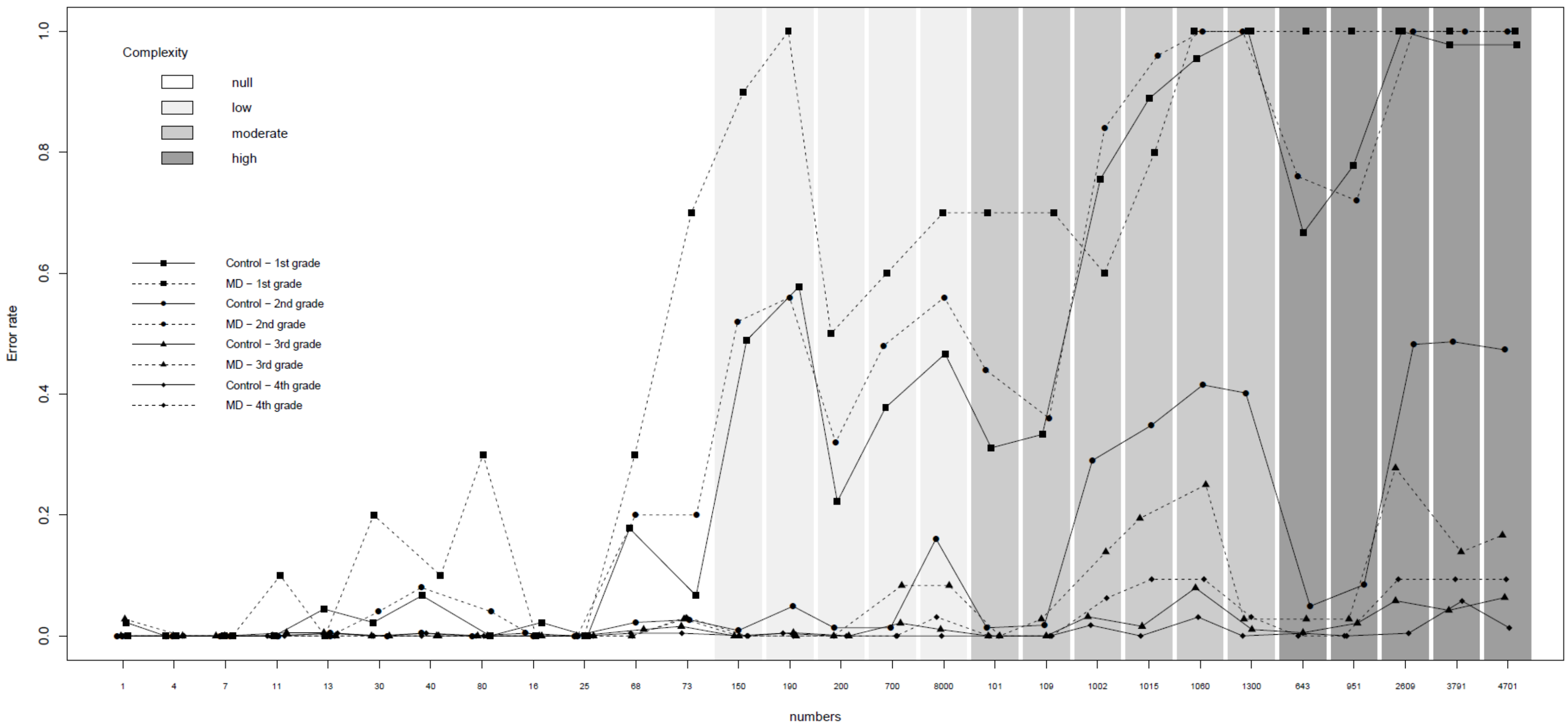

Figure 1 - Error rates on individual items according to children's group and school grade.

Task accuracy

Accuracy of the Arabic Number-Writing Task in discriminating children with mathematics difficulties was estimated with ROC analysis. Following the reference values for the area under the curve (AUC) established by Swets (1988), accuracy of Arabic Number-Writing Task in identifying children with mathematics learning difficulties is moderate in the 1st grade and high in the 2nd grade (AUC > 0.7; Table 3). However, in the next two grades the task did not show the same efficiency, achieving only a low accuracy in the 4th grade.

Table 3
ROC analysis.

Grade	AUC	Std. Error	*p*	Conf. interval (95%)				
				Lower	Upper	Cutoff	Spec.*	Sens.§
1	.791	.077	.004	.641	.941	14	.667	.700
2	.967	.014	< .001	.940	.994	20	.762	.880
3	.706	.053	< .001	.603	.809	27	.709	.639
4	.582	.060	.135	.464	.699	27	.849	.281
Global	.655	.031	< .001	.593	.716	27	.575	.650

* Specificity, § Sensitivity

Influence of syntactic complexity on transcoding performance

Previous studies showed that syntactic complexity has a strong impact on error rates in transcoding tasks (Camos, 2008; Moura et al., 2013). Here, we found a high correlation between the number of errors and the number of transcoding rules (r = 0.83 ; p < 0.001), which remains stable even when controlling for the variance due to the quantity of digits (r = 0.59; p < 0.001). To explore this relationship in deeper detail, a 3X2 ANOVA was run separately for each school grade. The analyses included error rates in the Arabic Number-Writing task in the three levels of syntactic complexity as within-subjects factor, and group as between-subjects factor. Whenever the assumption of sphericity was not satisfied, the Greenhouse–Geisser correction was applied to evaluate the p-values. To approximate a normal distribution, error rates were arcsine-transformed.

In the first grade, a main effect of syntactic complexity reflected an increase in error rates in function of the number of syntactic rules, and a main effect of group revealed higher error rates for children with mathematics difficulties (Table 4). Contrasts showed significant differences between all three levels of syntactic complexity (low vs. moderate: F[1, 53] = 8.37, MSE = 1.53, $p < .01$; η_p^2 = .14; moderate vs. high: F[1, 53] = 30.06, MSE = 3.85, $p < .001$; η_p^2 = .36). Moreover, an interaction between syntactic complexity and group was observed. Contrasts showed that the increase in error rates observed between low and moderate complexity was higher in control children (F[1, 53] = 5.58, MSE = 1.02, $p < .05$; η_p^2 = .09). Two post-hoc tests further explained this interaction, showing that controls had lower error rates in low complexity numbers (t[53] = 2.86, $p < .01$), but similar error rates in moderate complexity numbers (t[53] = 1.23, $p = .24$). The increase in error rates between numbers with moderate and high complexity was similar in the two groups (F [1, 53] = .54, MSE = .07, $p = .464$; η_p^2 = .01).

Table 4
Repeated measures ANOVA on transcoding errors according to group, school grade and syntactic complexity.

	Arabic number writing		
	F [df]	**MSE**	η_p^2
a) First grade			
Syntactic complexity	32.91 [2, 11]	2.71	.38***
Group	7.63 [1, 53]	.62	.13***
Syntactic complexity vs. Group	32.92 [2, 11]	.08	.01***
b) Second grade			
Syntactic complexity	83.44 [2, 49]	6.51	.25***
Group	153.36 [1, 25]	12.85	.38***
Syntactic complexity vs. Group	3.79 [2, 49]	.30	.02***
c) Third grade			
Syntactic complexity	17.36 [2, 446]	.45	.07***
Group	35.67 [1, 23]	.46	.14***
Syntactic complexity vs. Group	3.95 [2, 446]	.10	.02***
d) Fourth grade			
Syntactic complexity	9.61 [2, 510]	.14	.04***
Group	15.14 [1, 255]	.06	.06***
Syntactic complexity vs. Group	2.30 [2, 510]	.03	.009

WM = F value, partial Eta squared and significance values controlling for working memory differences
* p < 0.05. ** p < 0.01. *** p < 0.001
df = degrees of freedom

Main effects of group and syntactic complexity were also observed in the second grade. Again, repeated contrasts showed significant differences in error rates between the three levels of complexity (low vs moderate: F[1, 247] = 72.30, MSE = 10.54, p < .001; η_p^2 = .23; moderate vs high: F[1, 247] = 22.69, MSE = 2.23, p < .001; η_p^2 = .08). The interaction between group and syntactic complexity was again significant. Repeated contrasts revealed that the increase in error rates from low to moderate complexity was similar in both groups (F[1, 247] = .76, MSE =.11, p = .384; η_p^2 = .003). An increase in error rates from low to moderate complexity was higher in children with mathematics difficulties than in control children (F [1.247] = 4.71, MSE = .46, p < .05; η_p^2 = .02).

In the third grade, the effects of syntactic complexity, group, and the interaction between them were again significant. Contrasts revealed a significant increase in error rates when comparing numbers with low and moderate complexity (F[1, 223] = 30.91, MSE = 1.06, p < .001; η_p^2 = .12) but not when comparing numbers with moderate and high complexity (F [2, 223] = .40, MSE = .02, p = .526, η_p^2 = .002). Closer analysis of the significant interaction group vs. syntactic complexity reveals that children with mathematics difficulties showed a more pronounced increase in error rates from low to moderate complexity in comparison to control children (F [1, 223] = 9.90, MSE = .34, p < .01, η_p^2 = .04). Regarding the error rates observed when contrasting numbers with moderate and high complexity, the groups did not differ (F [1, 223] = .27, MSE = .02, p = .604, η_p^2 = .001).

In the fourth school grade, the two main effects group and syntactic complexity were significant, but not their interaction. Contrasts revealed a significant increase in the error rates of numbers with low and moderate complexity (F[1, 255] = 18.98, MSE = .24, p < .001; η_p^2 = .07). Nevertheless, numbers with moderate and high complexity did not differ in their error rates (F [1.25] = .60, MSE = .02, p = .439; η_p^2 = .002).

DISCUSSION

The purpose of this study was to examine the psychometric properties of a number transcoding task and its usefulness in screening mathematics learning difficulties in children in the early school years. The major findings revealed that the Arabic Number-Writing Task is a simple and powerful instrument for assessing children's basic number transcoding skills in early elementary school and discriminates children with and without mathematics learning difficulties with a high degree of sensitivity and specificity. The high reliability estimates of the transcoding task are promising regarding diagnostics and evaluation of cognitive interventions in mathematics difficulties. Moreover, closer item analysis revealed a strong impact of the number of rules necessary to transcode a number correctly on general task performance. Moreover, results indicate that the number of rules per item can explain most of the group differences observed between children with and without mathematics difficulties. In the following, these results will be discussed in deeper detail.

General test properties

High internal consistency coefficients were observed in the transcoding task in first and second grade children. For diagnostics purposes and evaluation of the impact of specific educational or neuropsychological interventions, these high reliabilities revert in a high precision in the characterization of individual performance (Huber, 1973). More specifically, the reliability coefficients observed in the present study in first and second grades can be considered invariant according to the criteria established by Willmes (1985) and can be used confidently to estimate confidence intervals for individual performance. Although the Arabic Number-Writing Task can be considered economic in its present format, particularly because of its flexibility regarding group testing and short duration, one may desire to reduce test length, particularly because of the relatively large number of very easy one-and two-digit items (see further discussion on this merit below). Test reduction seems to us to be practically feasible since the relevant item features responsible for item difficulty are well determined and the pool of suitable items in the numeric interval between three- and four-digits is large enough. In this context, the use of the number of rules necessary to transcode individual items as a criterion for the establishment of different groups of items is particularly important. The interaction between item complexity vs. mathematics difficulties observed in first to third grades illustrates this fact, since a difference in error rates between items with moderate and high complexity is present only in more capable children. One interpretation of the interaction results is that item discriminability in the transcoding task depends directly on the individual level of competence observed when children apply the conversion rules from verbal-to-Arabic formats. The present results suggest that the number of transcoding rules is a good criterion to distinguish the level of competence typical of children with and without mathematics difficulties. An adaptive version of the task could be constructed in which the number of rules necessary to transcode an item vary in an even more fine-grained scale than that employed in the present study.

Characterization of typical and atypical development of transcoding abilities

Overall, 1- and 2-digit numbers presented very low error rates in all school grades, regardless of children's mathematics abilities. These results are in line with the literature, which indicates that even kindergartners at risk for mathematics difficulties do not have troubles in transcoding small numbers (Landerl, Bevan, & Butterworth, 2004; van Loosbroek, Dirkx, Hulstijn, & Janssen, 2009) but can instead retrieve the Arabic forms directly from their long-term memory. Moreover, two-digit numbers also showed very low error rates in all school grades and are somewhat sensitive to mathematics difficulties only in first graders, but not in children in higher school grades.

In contrast, 3- and 4-digit numbers accounted for a large proportion of score variability, with high error rates being observed in the 1st grade and a steady decrease in higher grades. Interestingly, control children showed notable difficulties in transcoding 3- and 4-digit numbers until the 2nd grade, when children receive the formal instruction necessary for mastering the syntax of these numbers. Moreover, children with mathematics difficulties seem to demand a year longer than control children to master the same knowledge as control children. When analyzing the interactions between children's achievement and syntactic complexity in the ANOVA models, one observes that control children attending to the 3rd and 4th grades barely committed errors in the low complexity items. In turn, children with mathematical difficulties continue to present errors when they achieve the 3rd grade, although the error rates also decrease steadily over time. A delay in the acquisition of more complex transcoding rules has already been observed in children with mathematics difficulties (Moura et al., 2013), and typically developing children with lower working memory capacity (Camos, 2008). The present results corroborate this delay in the acquisition of transcoding rules observed in children with mathematics difficulties. To which extent these errors are also attributable to reduced working memory capacity has to be investigated in future studies.

The persistence of the effect of syntactic complexity in all grades constitutes strong evidence for the prominent role of transcoding rules in elucidating children's performance even in third and fourth grades. The rule knowledge as well as working memory ability have been identified as major mechanisms that contribute to number transcoding performance (Camos, 2008; Zuber, Pixner, Moeller, & Nuerk, 2009). There is evidence indicating that children with mathematics difficulties struggle in learning the more complex transcoding rules, as can be inferred from wrong frame errors (Moura et al., 2013). Wrong frame errors reflect the absence of knowledge of the magnitude intrinsic to each position in the digit sequence, that is, of place-value knowledge. Several studies have related the knowledge of place-value syntax with achievement in more complex numerical abilities, such as arithmetics (Mazzocco, Murphy, Brown, Rinne, & Herold, 2013; Moeller et al., 2011; Moeller, Pixner, Kaufmann, & Nuerk, 2009). Together, these pieces of evidence indicate that more abstract levels of numerical representation such as place-value knowledge can be assessed by means of the performance in transcoding task and reinforces its utility when trying to predict arithmetics abilities of individual children.

Together, the effect of syntactic complexity and the high correlation between error rates and the number of transcoding rules, suggest that working memory is an important variable associated to number writing. Working memory capacity has been associated in the transcoding research to storing the verbal string, searching in the long-term memory for lexical entries, parsing the previously non-acquired strings and applying the procedural rules (Barrouillet et al., 2004; Lochy & Sensabela, 2005). In previous research, we have also found this association between the number of rules and working memory, which suggests an implicit association between the syntactic complexity and working memory skills. Camos (2008) directly addressed this issue by investigating children with different verbal working memory abilities directly. These authors found a robust association between number of transcoding rules and the number writing performance as suggested by the ADAPT model. Moreover, Lopes-Silva, Moura, Julio-Costa, Haase and Wood (2014) showed that the influence of verbal working memory on number transcoding is mediated by phonemic awareness. According to the ADAPT model, phonological encoding is the first step in the number transcoding process. Further evidence suggests that visuospatial working memory capacity may be associated to syntactic transcoding errors related to the unit-decade inversion rule present in languages such as German, Dutch and Czech (Zuber, Pixner, Moeller, & Nuerk, 2009). These pieces of evidence indicate that the Arabic Number-writing task is theoretically grounded on a cognitive model with high content and construct validity.

Task discriminability

For the first time, diagnostic accuracy of Arabic Number-Writing Task was assessed by means of ROC analyses in the present study. Moderate and high accuracy estimates were observed in the first and second grades respectively, while in third and fourth grades the transcoding task did not show reliable indexes math difficulties. Therefore, Arabic Number-Writing Task may then be best suitable for screening children at risk of mathematics difficulties in the first two school grades but not in higher grades. Difficulties with number transcoding might remain traceable in children with mathematics difficulties in higher school grades, but the Arabic Number-Writing Task in its present format is too easy to be able to discriminate mathematics difficulties. It is possible that an adaptation of the task with the inclusion of more complex 5- and 6-digit numbers would be sufficient to guarantee sufficient group discriminability. However, it is also possible that the cognitive profile of mathematics difficulties, as measured by the Arabic Number-writing task, is not stable over time, so that difficulties experienced in early phases can be, eventually, overcome, and then new difficulties may appear (Geary, Hamson, & Hoard, 2000; Gersten, Jordan, & Flojo, 2005). If this is the case, good discriminability regarding mathematics difficulties may be limited to the first two school grades.

Future perspectives

A very interesting further development would be the design of an automatic algorithm for item generation, which allows the construction of more individualized versions of the Arabic Number-writing task, which is adaptive to the level of performance of single children (e.g. Arendasy, Sommer, Mayr, 2012) with and without mathematics difficulties. The ADAPT model provides a very valuable basis to generate items in all difficulty levels. The estimates of item difficulty obtained from large-sample studies such as the present one establish the basis for such further developments. Since transcoding tasks combine both diagnostic sensitivity and specificity regarding mathematics achievement with a solid theoretical basis of the cognitive mechanisms driving individual performance, automatic item generation may reveal to be very valuable in the construction of adaptive and flexible instruments best suitable not only to characterize individual performance but also to evaluate the impact of interventions designed to remediate the negative impact of mathematics difficulties on cognition and performance.

Practical implications

The good psychometric properties of the Arabic Number-writing Task together with its simple administration and consistent theoretical ground make of it a useful tool for assessing basic numerical skills of young children in both clinical and research contexts. The task may provide a quick and cheap way for screening first and second graders at risk of mathematical difficulties both collectively, at school, and individually, in clinical settings. The benefits of the early identification of children with possible major difficulties in mathematics are incommensurable. It enables early intervention efforts, thus minimizing future consequences of low numeracy, such as low incomes and less job opportunities (Bynner & Parsons, 1997).

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STUDY 2: TRANSCODING ABILITIES IN TYPICAL AND ATYPICAL MATHEMATICS ACHIEVERS: THE ROLE OF WORKING MEMORY, PROCEDURAL AND LEXICAL COMPETENCIES

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Abstract

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 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, the 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).

METHODS

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).

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).

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	0.42	
School type (% public)	11.1		14.3		0.2	1	0.91	
	Mean	*sd*	Mean	*sd*	*t*	*df*	*p*	*d*
Age (months)	115.25	12.72	113.11	16.15	0.71	107	0.48	0.16
Raven (z-scores)	0.36	0.61	0.37	0.66	-0.11	107	0.915	0.02
TDE Arithmetics	16.44	5.81	9.57	5.65	5.43	107	< 0.001	1.21
TDE Spelling	25.4	6.22	18.89	10	3.23	107	0.003	0.89
Digit Span (backward)	3.27	0.84	2.82	0.82	2.47	107	0.015	0.54
Corsi Span (backward)	4.17	1.03	3.86	0.97	1.41	107	0.16	0.51

df = degrees of freedom.

d = Cohen's effect size.

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 3x2x2 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.

Figure 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).

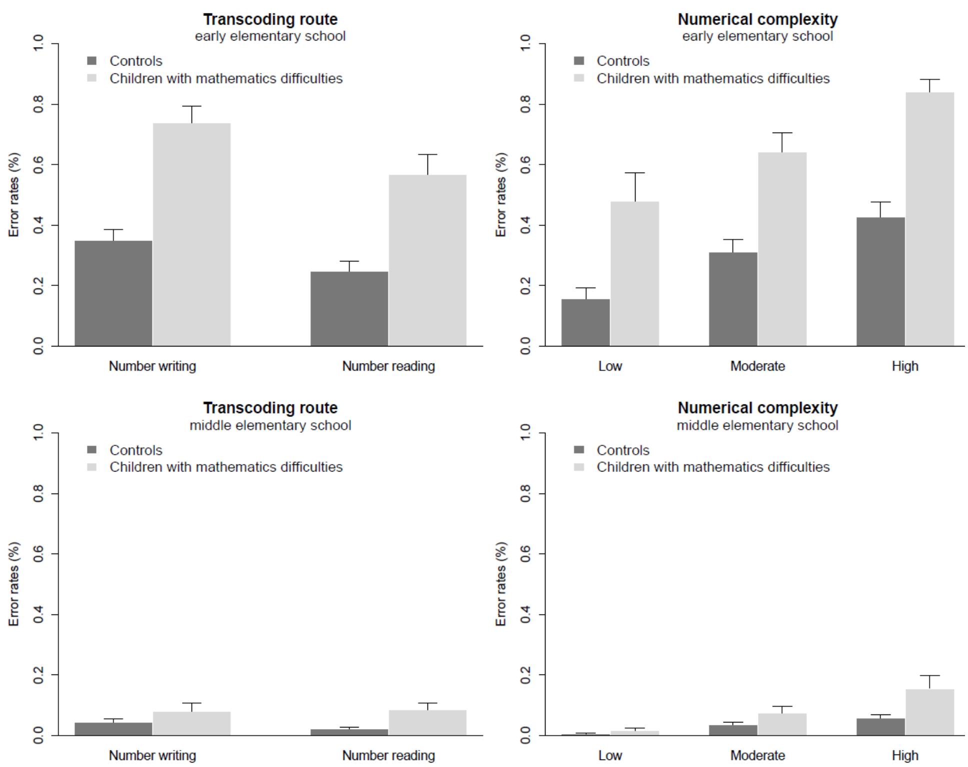

Figure 1. Error rates as a function of task, numerical complexity and children's group. Vertical bars depict standard error.

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.

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	0.45***	3.53 [2,70]	0.05	0.09*	25.19 [2,136]	0.08	0.27***	1.40 [2,132]	0.00	0.02
Task	19.11 [1,37]	0.22	0.34***	6.80 [1,35]	0.07	0.16*	0.44 [1,68]	0.00	0.01	0.79 [1,66]	0.00	0.01
Group	13.69 [1,37]	1.53	0.27***	6.44 [1,35]	0.61	0.15**	6.89 [1,68]	0.05	0.09**	6.07 [1,66]	0.05	0.08*
Complexity *vs.* Group	0.84 [2,74]	0.01	0.02	0.43 [2,70]	0.01	0.01	5.57 [2,136]	0.02	0.07**	4.82 [2,132]	0.01	0.07*

WM = *F*, partial Eta squared and significance values controlling for working memory differences.
df = degrees of freedom.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

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, 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 $R^2 = .36$, b's = –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 $R^2 = .20$, $b = –0.48$). 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]).

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.

Table 3

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

		Number Writing		Number Reading	
Grade	Error category (quantity of digits)	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 between brackets represent the mean error frequency (absolute frequency/n).
MD = Mathematics difficulties.

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 *p*’s > .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 *p*'s > .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 ($r = -.23$, $p < .05$).

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 2x2 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 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 *p*'s $< .01$; 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 ($r = -.26$, $p < .01$).

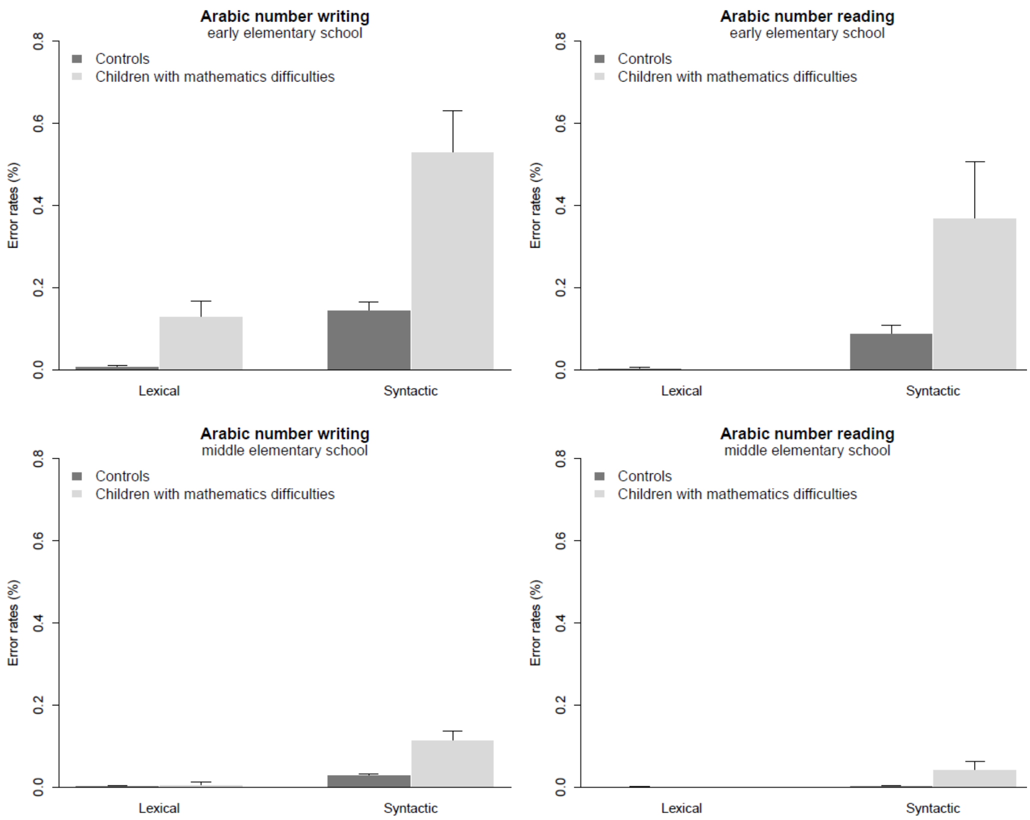

Figure 2. Relative frequency of lexical and syntactical errors according to children's group and transcoding task, vertical bars depict standard error.

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 2x2 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.

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	0.62***	9.90 [1,35]	0.05	0.22**	26.59 [1,37]	0.21	.42***	9.80 [1,35]	0.07	0.22**
Group	51.91 [1,37]	0.25	0.58***	36.68 [1,35]	0.00	0.51***	10.01 [1,37]	0.08	.21**	5.38 [1,35]	0.04	0.13*
Error category vs. Group	14.67 [1,37]	0.07	0.28***	8.91 [1,35]	0.04	0.20**	10.95 [1,37]	0.08	.23**	6.01 [1,35]	0.04	0.15*
Middle elementary school												
Error category	98.91 [1,68]	0.03	0.59***	6.51 [1,66]	0.00	0.09*	16.34 [1,68]	0.00	0.19***	0.31 [1,66]	0.00	0.00
Group	28.67 [1,68]	0.01	0.30***	25.88 [1,66]	0.01	0.28***	12.42 [1,68]	0.00	0.15**	13.06 [1,66]	0.00	0.16**
Error category vs. Group	37.29 [1,68]	0.01	0.35***	34.12 [1,66]	0.01	0.34***	13.31 [1,68]	0.00	0.16**	14.14 [1,66]	0.00	0.18***
b. Analysis of syntactic errors												
Early elementary school												
Error category	34.10 [2.74]	0.22	0.48***	5.84 [2,70]	0.04	0.14*	7.57 [2,74]	0.11	0.17**	1.68 [2,70]	0.02	0.05
Group	47.93 [1,37]	0.22	0.56***	33.17 [1,35]	0.13	0.49***	19.93 [1,37]	0.16	0.35***	13.30 [1,35]	0.1	0.27**
Error category vs. Group	12.20 [2.74]	0.08	0.25***	7.61 [2,70]	0.05	0.18*	4.24 [2.74]	0.06	0.10*	2.75 [2,70]	0.04	0.07
Middle elementary school												
Error category	2.44 [2,136]	0.00	0.04	0.18 [2,132]	0.00	0.00	15.11 [2,136]	0.00	0.18***	0.36 [2,132]	0.00	0.00
Group	10.52 [1,68]	0.00	0.13**	9.32 [1,66]	0.00	0.12**	12.57 [1,68]	0.00	0.16**	11.89 [1,66]	0.00	0.15**
Error category vs. Group	1.27 [2,136]	0.00	0.02	1.35 [2,132]	0.00	0.02	12.01 [2,136]	0.00	0.15***	12.39 [2,132]	0.00	0.16**
c. Analysis of "0" related errors in the Arabic number writing task												
Early elementary school												
Error category	14.76 [1,37]	0.05	0.28***	0.53 [1,35]	0.00	0.01	-	-	-	-	-	-
Group	18.72 [1,37]	0.09	0.34***	11.94 [1,35]	0.00	0.25**	-	-	-	-	-	-
Error category vs. Group	6.36 [1,37]	0.02	0.15*	6.54 [1,35]	0.02	0.16*	-	-	-	-	-	-

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

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.

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Appendix A

The twenty-eight items from the Arabic number reading task according to ADAPT category, quantity of transcoding rules and complexity level.

	Arabic number reading							
Item	Number	Category	Rules	Complexity level	Missings	Error (raw)	Error Rates Controls*	Error Rates Mathematic Difficulties group*
1	3	U	2	-	0	0	0.00	0.00
2	6	U	2	-	0	0	0.00	0.00
3	8	U	2	-	0	0	0.00	0.00
4	12	P	2	-	0	0	0.00	0.00
5	14	P	2	-	0	1	0.00	0.04
6	50	D	2	-	0	0	0.00	0.00
7	20	D	2	-	0	1	0.00	0.04
8	47	DU	2 (3)	-	0	0	0.00	0.00
9	15	P	2	-	0	2	0.00	0.07
10	92	DU	2 (3)	-	2	1	0.00	0.07
11	80	D	2	-	2	1	0.00	0.04
12	19	DU	2 (3)	-	0	2	0.00	0.07
13	105	HU	4	moderate	2	4	0.02	0.11
14	800	UH	3	low	5	6	0.06	0.18
15	160	HD	3	low	2	6	0.04	0.14
16	2000	UM	3	low	12	13	0.10	0.25
17	400	UH	3	low	3	4	0.02	0.11
18	102	HU	4	moderate	2	4	0.02	0.11
19	170	HD	3	low	2	7	0.06	0.11
20	1004	MU	4	moderate	3	15	0.12	0.25
21	432	UHDU	4 (5)	high	4	6	0.05	0.18
22	567	UHDU	4 (5)	high	4	6	0.07	0.11
23	1013	MP	4	moderate	4	16	0.14	0.25
24	8304	UMUHU	7	high	8	26	0.22	0.50
25	1070	MD	4	moderate	4	20	0.15	0.39
26	5601	UMUHU	7	high	7	31	0.26	0.57
27	1900	MUH	4	moderate	4	16	0.10	0.39
28	5962	UMUHDU	6 (7)	high	6	23	0.19	0.46

Note. Description of each item according to its category (U, unit; P, particular; D, decade; H, hundred; M, thousand), quantity of transcoding rules (DU's specified when directly retrieved and algorithmically transcoded - between parentheses) and complexity level. The "Missings" column represents missing data.
* Relative frequencies of error rates.

Appendix B

The twenty-eight items from the Arabic number writing task according to ADAPT category, quantity of transcoding rules and complexity level.

Item	Arabic number writing							
	Number	Category	Rules	Complexity level	Missings	Error (raw)	Error rates Controls*	Error Rates Mathematic Difficulties group*
1	4	U	2	-	0	0	0.00	0.00
2	7	U	2	-	1	0	0.00	0.00
3	1	U	2	-	1	0	0.00	0.00
4	11	P	2	-	1	0	0.00	0.00
5	40	D	2	-	0	3	0.00	0.11
6	16	DU	2 (3)	-	0	0	0.00	0.00
7	30	D	2	-	0	3	0.01	0.07
8	73	DU	2 (3)	-	2	6	0.04	0.11
9	13	P	2	-	1	0	0.00	0.00
10	68	DU	2 (3)	-	1	6	0.01	0.18
11	80	D	2	-	1	1	0.00	0.04
12	25	DU	2 (3)	-	1	1	0.00	0.04
13	200	UH	3	low	2	6	0.05	0.07
14	109	HU	4	moderate	2	6	0.02	0.14
15	150	HD	3	low	2	11	0.05	0.25
16	101	HU	4	moderate	2	7	0.02	0.18
17	700	UH	3	low	2	6	0.02	0.14
18	643	UHDU	4 (5)	high	5	13	0.06	0.29
19	8000	UM	3	low	2	12	0.09	0.18
20	190	HD	3	low	4	8	0.05	0.14
21	1002	MU	4	moderate	2	25	0.21	0.29
22	951	UHDU	4 (5)	high	3	13	0.06	0.29
23	1015	MP	4	moderate	2	22	0.17	0.29
24	2609	UMUHU	7	high	4	37	0.28	0.50
25	1300	MUH	4	moderate	4	28	0.22	0.36
26	3791	UMUHDU	6 (7)	high	7	33	0.28	0.36
27	1060	MD	4	moderate	5	31	0.26	0.36
28	4701	UMUHU	7	high	2	34	0.25	0.50

Note. Description of each item according to its category (U, unit; P, particular; D, decade; H, hundred; M, thousand), quantity of transcoding rules (DU's specified when directly retrieved and algorithmically transcoded - between parentheses) and complexity level. The "Missings" column represents missing data.
* Relative frequencies of error rates.

STUDY 3: PHONEMIC AWARENESS AS A PATHWAY TO NUMBER TRANSCODING.

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Abstract:

Although verbal and numerical abilities have a well-established interaction, the impact of phonological processing on numeric abilities remains elusive. The aim of the study is to investigate the role of phonemic awareness in number processing and to explore its association to other functions such as working memory (WM) and magnitude processing. One hundred and seventy two children from 2nd to 4th grade were evaluated regarding their intelligence, number transcoding, phonemic awareness, verbal and visuospatial WM and number sense (nonsymbolic magnitude comparison) performance. All of the children had normal intelligence. Among these measurements of magnitude processing, WM and phonemic awareness, only the last one was retained in regression and path models predicting transcoding ability. Phonemic awareness mediated the influence of verbal WM on number transcoding. Evidence points out that phonemic awareness is responsible for a significant impact on number transcoding. Such association is robust and should be taken into account in cognitive models of both dyslexia and dyscalculia.

INTRODUCTION

Mastering reading and writing numbers in their verbal and Arabic forms is an essential skill for daily life (Lochy and Censabella, 2005). Being able to manipulate numbers and convert them from one format into another is one of the first steps in children's mathematical learning and starts to be formally trained in kindergarten. The ability to establish a relationship between the verbal and Arabic representations of number, when a conversion of numerical symbols from one notation to the other is necessary, is called number transcoding (Deloche and Seron, 1987).

The verbal number system is linguistically structured and, although it may differ among languages, there are some common basic principles and regularities (Fayol and Seron, 2005). It is typically composed of a lexicon of single words that designate a few quantities (like *five*, *eleven*, *seventy* and *hundred*) and organized by a syntax that arranges these lexical units in order to represent any possible quantity. The two basic syntactic principles are the relations of addition and multiplication. In this sense, numbers are represented as sum relationships (e.g.: *eighty-one* means *eighty* plus *one*) and product relationships (e.g.: *three hundred* means three times *hundred*). The number words in Portuguese are similar to the English number words in the sense that they are also organized in lexical classes for units, decades and particulars (the -*teens* in English) (Wood et *al.,* 2006).

The Arabic code is more complex and is acquired later in development (Geary, 2000). Its lexicon is composed of only a small set of different symbols (digits from 0 to 9), and the basic syntactic principle that combines them to form all numbers is the positional value (or place-value). According to this principle, the digit's value depends on its position in the numerical string and is given by a power of base ten. Therefore, in the case of three-digit numbers, the first digit (from right to left) is multiplied by 10^0, the second by 10^1, and so on. The number 124, for example, represents a quantity equal to $1 \times 10^2 + 2 \times 10^1 + 4 \times 10^0$ (or 100 + 20 + 4). The digit 0 has a special syntactic role when it denotes the absence of a given power of ten, as occurs in numbers with internal zeros, for example the number 406 (4×10^2

$+ 0 \times 10^1 + 6 \times 10^0$).

One preeminent model of number transcoding is ADAPT (A Developmental, Asemantic, and Procedural model for Transcoding from verbal to Arabic numerals; Barrouillet et al., 2004). According to ADAPT, the inputs are coded into a phonological sequence and the parsing mechanisms then subdivide this sequence into smaller units to be processed by a production sys-tem. This production system is related to rules devoted to the retrieval of Arabic forms from long-term memory (LTM) (called P1 rules), to managing the size of digit chains (P2 and P3 rules, which create a frame of two or three slots) and to filling these slots (if there are any empty slots, P4 rules will fill them with 0s). Separators, such as thousands and hundreds, are used to identify the number of slots; once every segment is placed in its digit form in the chain, it is transcribed. The model accounts for the development of transcoding processes through practice: experience leads to an expansion of the numerical lexicon and improvement of conversion rules.

The ADAPT model is the only cognitive model of number transcoding which makes testable predictions regarding both working memory capacity and phonological/lexical representations and their respective roles in the typical and atypical development of transcoding abilities. Moreover, even though it is not explicitly stated in the original publication (Barrouillet et al., 2004), ADAPT clearly emphasizes the importance of phonological encoding in the first steps of number writing production, and this has not been investigated in more detail. Because both working memory and the ability to form lexical representations of numbers and, as we assume here, phonemic awareness are related to mathematical performance, ADAPT is the only transcoding model directly examined in the present study.

Short-term memory and working memory (thereafter WM) are involved in the temporary storage of verbal information, lexical retrieval, and the execution of the manipulations to generate the Arabic output. Working memory representations are also involved in creating a sequence of digits and possibly blank spaces to be filled with subsequent procedures. It has been consistently related to number transcoding performance and error patterns (Camos, 2008; Zuber et al., 2009; Pixner et al., 2011). The role of working memory in transcoding tasks can be outlined in the following steps: encoding the number to be transcoded; monitoring the application of transcoding rules and the production of the numeral (Lochy and Censabella, 2005).

Another cognitive mechanism that may be involved in number transcoding is phonemic awareness. Phonemic awareness is the subcomponent of phonological processing which is related to the ability to perceive and manipulate the phonemes that constitute words (Wagner and Torgesen, 1987). According to the ADAPT model (Barrouillet et al., 2004), the phonological encoding of the verbal numerals is the primary step in transcoding procedures, before the use of algorithm rules and retrieval from LTM. Therefore, limitations in phonological processing capacity may constrain the ability to transcode, particularly in the case of longer and more complex numbers. Phonological processing may also interact with the capacity of verbal working memory. The more demanding the phonological processing of numerical stimuli, the fewer resources would remain available in verbal working memory for transcoding. Although the conversion of a verbal representation to an Arabic one is related to phonological representations, this association has not yet been investigated in detail in the ADAPT model.

Krajewski and Schneider (2009) found that phonological awareness facilitates the differentiation and manipulation of single words in the number word sequence. These authors built a model of early arithmetic development that postulates three different levels: (1) basic numerical skills, in which children are already able to discriminate between quantities and to recite number words, without accessing their quantitative semantic meaning; (2) quantity-number concept, when there is a linkage between magnitudes and the number words that represent them; (3) number relationships, the point at which children understand that the difference between two numbers is another number.

According to these authors, phonological awareness (measured by phoneme synthesis and rhyming tasks) plays an important role in the first level. The authors claim that because this phonological skill is related to the ability to differentiate and manipulate meaningful segments of language, it is also important in differentiating number words (“one,” “two,” “three” instead of “onetwothree”).

In view of the above, the aim of this study is to investigate the role of specific cognitive mechanisms underlying number transcoding such as general cognitive ability, verbal and non-verbal short-term and working memory, magnitude representation, and phonemic awareness. More specifically, our main goal was to investigate the relative impact of phonemic aware-ness on number transcoding. Phonemic awareness is related to reading and spelling skills (Wagner and Torgesen, 1987; Castles and Coltheart, 2004; Hulme et al., 2012; Melby-Lervå et al., 2012), and recent studies have also focused on its association with arithmetic fact retrieval and with arithmetic word problems (Hecht et al., 2001; Boets and De Smedt, 2010; De Smedt et al., 2010). Importantly, many measures of phonemic awareness, such as the phoneme elision task employed in the present investigation, require a certain availability of working memory resources. Working memory is recruited in such tasks when the participant must hold a word in mind while determining the phonological information to be deleted (De Smedt et al., 2010). Both verbal and visuospatial working memory play important roles in numerical transcoding according to the ADAPT model (Camos, 2008; Zuber et al., 2009), but no study so far has investigated the specific contribution of phonemic awareness and working memory in number transcoding tasks.

Two main hypotheses will be addressed in the present study: First, based on the central role assigned by the ADAPT model to working memory capacity (Barrouillet et al., 2004; Camos, 2008), one can argue that working memory contributes to number transcoding independently because working memory capacity is putatively implicated in the use of transformation rules and procedures employed during transcoding. Second, at least part of the influence of working memory on number transcoding should be mediated by phonemic awareness. Phonemic aware-ness scores are assumed to index the quality of the underlying phonological representations. These representations are related to the perception and manipulation of sound-based processes (Simmons and Singleton, 2008); therefore, phonemic awareness performance would have an impact on verbal working memory and transcoding skills.

MATERIALS AND METHODS

The study was approved by the local research ethics committee (COEP–UFMG) and is in line with the Declaration of Helsinki. Children participated only after informed consent was obtained. Informed consent was obtained in written form from parents and orally from children.

Sample

A total of 487 children in grades 2–4 were invited from public schools in Belo Horizonte, Brazil. Of these children, 207 (42%) children agreed to take part in this study. Testing was conducted in the children's own schools. The various tasks were presented in four different pseudo-random orders during one session that lasted approximately 1 h.

We excluded five children from the sample due to low intelligence (performance on Raven's Colored Progressive Matrices below one standard deviation). One child did not complete the entire battery and was also excluded from the analysis. Twenty-nine children were excluded from further analyses because either they had a poor R^2 on the fitting procedure to calculate their internal Weber fraction on the non-symbolic comparison task ($R^2 < 0.2$) or they showed an internal Weber fraction that exceeded the limit of discriminability of the non-symbolic magnitude comparison task ($w > 0.6$). The final sample comprised 172 children (55.2% girls), with a mean age of 111.84 months ($SD = 10.90$), ranging from 94 to 140 months.

Instruments

The following instruments were used in the cognitive assessment: Raven's Colored Progressive Matrices, Digit Span, Corsi Blocks, Non-symbolic magnitude comparison task, Phoneme Elision and Arabic number writing task.

(a) Raven's Colored Progressive Matrices: general intelligence was assessed with the age-appropriate Brazilian validated version of Raven's Colored Matrices (Angelini et al., 1999). The analyses were based on z-scores calculated from the manual's norms.

(b) Digit Span: Verbal short-term and working memory were assessed with the Brazilian WISC-III Digit Span subtest (Figueiredo, 2002). Performance in the forward order was considered a measure of verbal short-term memory, and the backward order was used to assess verbal working memory (Figueiredo and Nascimento, 2007). We evaluated the total score (correct trials x span) in both the forward and backward orders.

(c) Corsi Blocks: This test is a measure of the visuospatial component of short-term and working memory. It consists of a set of nine blocks, which the examiner taps in a certain sequence. The test starts with sequences of two blocks and can reach a maximum of nine blocks. We used the forward and backward orders according to Kessels et al. (2000). In the for-ward condition, the child is instructed to tap the blocks in the same order as the examiner, and in the backward condition, in the reverse order. We also evaluated the total scores.

(d) Non-symbolic magnitude comparison task: In this task, the participants were instructed to compare two simultaneously presented sets of dots, indicating which one contained the larger number. Black dots were presented on a white circle over a black background. In each trial, one of the two white circles contained 32 dots (reference numerosity) and the other contained 20, 23, 26, 29, 35, 38, 41, or 44 dots. Each magnitude of dot sets was presented eight times. The task comprised 8 learning trials and 64 experimental trials. Perceptual variables were varied such that in half of the trials the individual dot size was held constant, while in the other half, the size of the area occupied by the dots was held constant (see exact procedure descriptions in Dehaene et al., 2005). Maximum stimulus presentation time was 4.000 ms, and the inter-trial interval was 700 ms. Before each trial, a fixation point appeared on the screen: a cross, printed in white, with each line 30 mm long. If the child judged that the right circle presented more dots, a predefined key localized in the right side of the keyboard should be pressed with the right hand. However, if the child judged that the left circle contained more dots, then a predefined key on the left side had to be pressed with the left hand (Costa et al., 2011). As a mea-sure of the number sense acuity, the internal Weber fraction (w) was calculated for each child based on the Log-Gaussian model of number representation (Dehaene, 2007), with the methods described by Piazza et al. (2004).

(e) Phoneme Elision: This is a widely accepted measure of phonemic awareness (Wagner and Torgesen, 1987; Castles and Coltheart, 2004; Hulme et al., 2012; Melby-Lervå et al., 2012). The child hears a word and must say what the word would be if a specified phoneme in the word were to be deleted (e.g., "*filha*" without /f/ is "*ilha*" [in English, it would be similar to "cup" without /k/ is "up"). The test comprises 28 items: in 8 items, the child must delete a vowel, and in the other 20, a consonant. The consonants to be suppressed varied by place and manner of articulation. The phoneme to be suppressed could be in different positions within the words, which ranged from 2 to 3 syllables. The internal consistency of the task is 0.92 (KR-20 formula).

(f) Arabic number writing task: To evaluate number transcoding, children were instructed to write the Arabic forms of dictated numbers. This task consists of 40 items, up to 4 dig-its (3 one-digit numbers, 9 two-digit numbers, 10 three-digit numbers and 18 four-digit numbers). The one- and two-digit numbers were classified as "lexical items" (12 items), and the other 28 items require the use of algorithm-based rules in order to be written (Barrouillet et al., 2004; Camos, 2008). This task has been used in a previous study with a comparable sample, and the consistency of this task was KR-20 = 0.96 (Moura et al., 2013).

Analysis

The differential impact of phonemic awareness and working memory on number transcoding was investigated in a hierarchical regression analysis with Arabic number writing as the dependent variable. Age and intelligence were entered first, and working memory and the Weber fraction in a second step, using the stepwise method. The phoneme elision task was entered in the model in a third step, also using the stepwise method. This allowed us to investigate the specific contribution of phonemic awareness to number transcoding performance after working memory variance was taken into account.

As a complement, path analyses, including all measures of age, intelligence, working memory and phonemic awareness were calculated, to determine the specific contribution of phonemic awareness as a mediator of the effect of working memory on number transcoding.

RESULTS

Thirty-three percent of the children did not commit any errors in the number transcoding task. Ninety-three percent of the children did not commit any errors on the numbers that can be lexically retrieved (items 1–12). According to what is suggested by the ADAPT model, errors rates increased with the number of rules required for number transcoding. In the numbers that required 3 transcoding rules, 50% of the children com-mitted errors, in the 4-rules, 71.6% presented some errors, in the 5-rules, 73.3% and, finally in the more complex items (6 and 7 rules), 84.5% of the children committed, at least, one error.

Since one-third of the sample did not commit any error in the transcoding task, one may argue that they should be excluded from the sample to avoid biases in the estimation of the covariance matrix, particularly with regard to the association between transcoding performance and other cognitive functions. To investigate the occurrence of bias, regression and path analyses were performed in the full sample and in the sample without the children with perfect score in the transcoding task. Results were numerically comparable in both regression and path analyses and their interpretation was exactly the same. For this reason, we decided to report the results obtained by analyzing the full sample.

Association between cognitive variables and transcoding ability

First, the specific impact of the different cognitive mechanisms on number transcoding was evaluated by means of hierarchical regression models. To approximate a normal distribution, error rates of the Arabic number writing task were arcsine transformed. Initially, we examined the general association between these measures through Pearson's correlations. Inspection of Table 1 reveals that the error rates observed in the number transcoding task were negatively correlated to age, intelligence, working memory, and phonemic awareness. There was also a weak positive correlation between error rates in number transcoding and the Weber fraction, which may reflect the maturation level of more general numerical skills. Moreover, phonemic awareness was significantly correlated to intelligence and working memory.

Table 1. Correlations between the neuropsychological measures

	1	2	3	4	5	6	7	8
1. Age (in months)	1							
2. Raven	-.23**	1						
3. Digit Span-Forward	.19*	.19*	1					
4. Digit Span-Backward	.05	.34**	.18*	1				
5. Corsi Blocks Forward	.19*	.28**	.15*	.20**	1			
6. Corsi Blocks Backward	.01	.34**	.14	.36**	.36**	1		
7. Weber fraction	-.19*	-.11	-.17*	-.19*	-.16*	-.13	1	
8. Phoneme elision	.11	.36**	.23**	.36**	.24**	.25**	-.13	1
9. Number Transcoding	-.11	-.17*	-.11	-.15*	-.10	-.13	.21**	-.36**

**. Correlation is significant at the 0.01 level (2-tailed)
*. Correlation is significant at the 0.05 level (2-tailed)

To investigate in more detail the specific impact of phone-mic awareness on transcoding abilities, a hierarchical regression model was calculated (Table 2). In this model, more general determinants of cognitive development were entered first, and more specific predictors of transcoding ability were included later on, in a hierarchical fashion. In step 1, age and intelligence were included as general factors that predict school achievement, using the enter method. In step 2, the following cognitive measures were included: Weber fraction and the total scores of the forward and backward orders of Digit Span and Corsi Blocks. Last, in step 3, we included the phoneme elision score. The stepwise method was used in steps 2 and 3 to avoid redundancy and to guarantee a high degree of parsimony.

The regression model reveals that after removing the effects of age and intelligence in step 1, verbal working memory remains a significant predictor of transcoding performance in step 2. Nevertheless, the addition of phonemic awareness to the model in step 3 leads to the exclusion of verbal working memory. Phonemic awareness, along with age and intelligence, was a significant predictor of number transcoding and absorbed the impact of verbal working memory on transcoding performance. The model explains a moderate amount of variance (Table 2). Measures of the approximate number system, visuospatial short-term memory, and visuospatial working memory were not retained in the model.

Table 2. Regression Analysis for Number Transcoding (errors Arcsine, adjusted r^2= 0.41).

Predictor	**beta**	**Partial t**	**sig**	**r^2 change**
Intercept		10.14	<.001	
Age (months)	-0.404	-6.487	<.001	0.305
Raven	-0.225	-3.282	0.001	
Digit Span-Backward	-0.089	-1.358	0.176	excluded
Weber fraction	0.095	1.545	0.124	excluded
Digit Span-Forward	-0.056	-0.885	0.378	excluded
Corsi Blocks-Backward	-0.035	-0.529	0.598	excluded
Corsi Blocks-Forward	-0.003	-0.051	0.959	excluded
Phoneme elision	-0.337	-5.038	<.001	0.088

The reason to employ a hierarchical regression model in this analysis is to demonstrate the validity of the present experimental setup. By entering the measures of working memory in the regression model first we are able to replicate previous studies and thereby show that our measures of working memory were well-chosen and are associated to transcoding abilities. After completing this step of validation of well-established results, we continue the investigation showing that phonemic awareness absorbs the impact of measures of working memory on transcoding capacity. We have also calculated a regression model allowing the effect of phonemic awareness to vary simultaneously to measures of working memory, that is, with no hierarchical distinction between these variables. Results were largely comparable with those reported previously: only phonemic awareness is retained in the model along with intelligence and age (R^2 = 0.64; adjusted R^2 = 0.40; b = −0.02).

Describing the roles of phonemic awareness and verbal memory in Arabic number transcoding

As shown in the previous section, the influence of the verbal working memory on number transcoding is shared with phonemic awareness. Therefore, as a complement to the previous findings, path analyses including both working memory and phonemic awareness, as well as Weber fraction, were calculated in order to investigate the interplay of these variables in number transcoding.

To determine the strength of the effect of phonemic awareness on number transcoding, a sequence of models was calculated and compared. Chi-square and the approximate fit indexes root mean square residual (RMR), goodness of fit index (GFI), adjusted goodness of fit index (AGFI), comparative fit index (CFI) and root mean square error of approximation (RMSEA) were used to evaluate model quality. A non-significant chi-square indicates no significant discrepancy between model and data. The RMR measures the ratio of residuals in comparison to the covariances expressed by the models. Values smaller than 0.10 are considered adequate. GFI, AGFI, and CFI evaluate the degree of misspecification present in the model. Usually, the best accept-able values are greater than 0.90. Finally, the Root

Mean Square Error of Approximation, or RMSEA, considers the model complexity when evaluating the model fit. The RMSEA is considered acceptable when it is lower than 0.05. The Chi-square difference between models was employed to compare models with increasing numbers of free parameters. Models were calculated in the software AMOS v.19 using the maximum likelihood estimation function.

To control for the influence of developmental and intellectual levels on the path models, we calculated the unstandardized residuals of the independent variables (short-term and working memory, Weber fraction and phonemic awareness), in which the portion of variance due to age (in months) and/or intelligence was removed. These adjusted values of working memory, magnitude processing and phonemic awareness were entered as the exogenous variables in the path analyses. All the covariances between the exogenous variables were set as free (Figure 1).

Those variables with negative standardized values indicate that higher scores in these predictors lead to lower error rates in the number transcoding task. The only exception is the Weber Fraction path, in which higher values indicate poorer magnitude representation acuity and, hence, more errors in number transcoding.

Fit statistics of path models are shown in Table 3. The first and most complex model (ALL PATHS) included the two measures of short-term and working memory (forward and backward versions of Digit Span and Corsi Blocks), as well as Weber fraction and an additional Phoneme Elision mediation path between both the forward and backward versions of the Digit Span and the number writing tasks. This model presented adequate fit indexes but is not parsimonious. Models with fewer parameters to be estimated were designed and were compared to the ALL PATHS model and to one another.

First, the NO VISUOSPATIAL model removed the paths from visuospatial memory to transcoding. Accordingly, the NO ANS model also suppressed the path from the Weber fraction to transcoding. In one further step, two models were calculated. In the first (MEDIATION PATH), the contribution of verbal working memory to transcoding is partially mediated by phone-mic awareness. Finally, to determine the relevance of phonemic awareness for transcoding, in the last model, the path from Phoneme elision to Number transcoding was removed, while the direct paths from verbal working memory to transcoding were retained (NO MEDIATION). If the exclusion of any of these paths leads to a statistically significant decrease in model fit, one may conclude that the specific parameters removed from the more parsimonious version of the path model contribute substantially to model fit.

Inspection of Table 3 reveals that all models including the Phoneme Elision-mediation path reached satisfactory fit levels. Nevertheless, all models presented large residuals, as indicated by the RMR, which suggests that the variables included in the models were not sufficient to fully explain the variance in the number writing task. However, non-significant Chi-squares and the other fit measures associated with these models were largely acceptable.

Overall, the model that presented the worst fit indices was the one that excluded the Phoneme Elision-mediation path and assumed that Digit Span has a direct influence on number transcoding (NO MEDIATION). Model comparisons corroborate these results because the model NO MEDIATION presented statistically poorer fit than all other models. Its chi-square was statistically significant, and the model did not present any adequate fix indexes (Table 3). This finding suggests that phonemic aware-ness is a relevant predictor of transcoding performance, with substantial specific contribution. Moreover, comparisons among all other models only produced non-significant chi-square differences. Given the statistical equivalence of these models, one may select the model MEDIATION PATH, in which the effect of working memory on transcoding performance is partially mediated by phonemic awareness, as the most parsimonious description of the present data. Importantly, the association between verbal working memory and phonemic awareness is stronger than that between verbal short-term memory and phonemic awareness. Regression values of the model MEDIATION PATH are depicted in Figure 1.

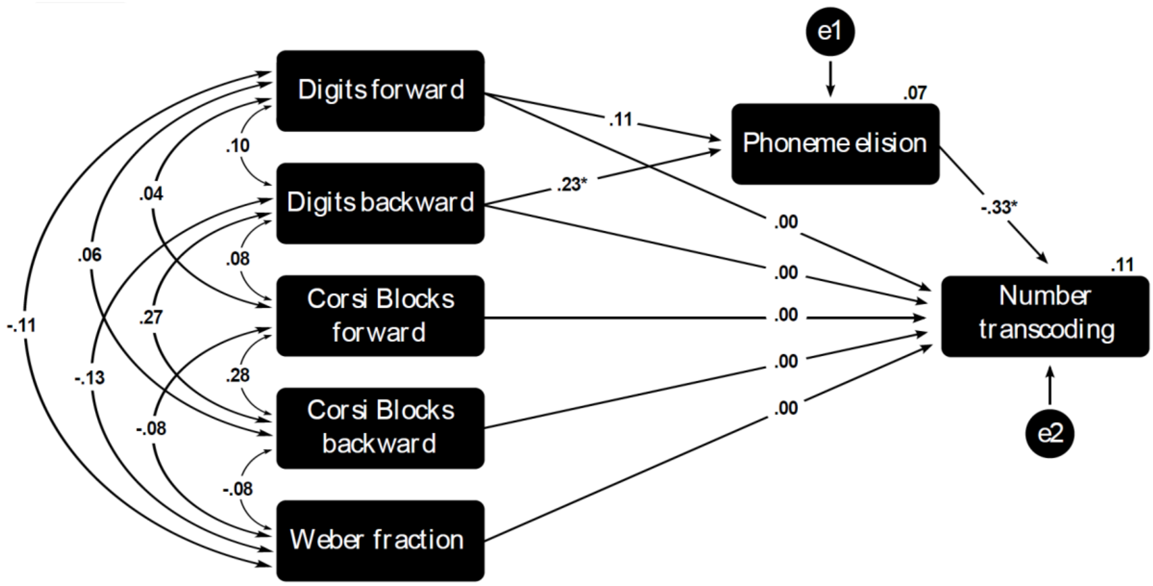

Figure 1 – Path-analysis model describing the effects of working memory, Weber fraction and phonemic awareness in a number transcoding task

Note. Paths marked with * are significant at the level 0.05 and with ** are significant at the level 0.001.

DISCUSSION

The present study investigated the impact of phonological skills on a number transcoding task, and it is, to our knowledge, the first to simultaneously evaluate the relative impact of short-term and working memory, number sense and phonemic awareness on number transcoding. Our results revealed two main findings. First, we confirmed previous evidence of a verbal working memory effect on number transcoding, and, more importantly, we provided evidence of a relationship between number transcoding and phonemic awareness. Our second main finding is that the well-established relationship between verbal working memory capacity and number transcoding is mediated by phonemic awareness abilities. In the following sections, these topics will be discussed in more detail.

The impact of verbal and visuospatial working memory on Arabic number writing

The performance of children in the number writing task was far from being flawless. They present many errors on the more complex two-, three-, and four-digit items, which require more than three transcoding rules, according to ADAPT. These findings are in accordance to what has been reported in the literature regarding transcoding skills of school aged children (Moura et al., 2013) and have been interpreted as a product of working memory processes in number transcoding (Camos, 2008). However, little is effectively known about the selective impact of different components of working memory on number transcoding. To our knowledge, this was the first study to analyze this problem in greater depth. Although a specific role of the central executive function in transcoding has been suggested (Camos, 2008), the present study is the first to explore the impact of phonological and visuospatial working memory in a number writing task and distinguish them from the central executive. We provide evidence regarding the specific role of phonological working memory and, more precisely, of the quality of underlying phonological representations, by means of the phonemic aware-ness performance.

Working memory plays an important role in the algorithmic-based procedures of number transcoding (Camos, 2008; Pixner et al., 2011). Essentially, it is believed to be involved in the maintenance of verbal units from the verbal numbers and in managing the new digit chain. In our study, we found that better verbal working memory capacity was associated with higher number transcoding performance. Interestingly, the same does not apply to the visuospatial components of short-term and working memory, as none of them revealed an association with transcoding performance in correlation, regression or path analyses. In a previous study by Zuber et al. (2009), the visuospatial working memory component was associated with the management of Arabic code syntax. Nevertheless, it is important to note here that the sample used in this other study was composed of German-speaking first graders, and the German number word system is different from the Portuguese system. In German, the order of the units and decades in the verbal numerals is inverted in comparison to the Arabic ones. One possibility, therefore, is that transcoding numbers in

Portuguese demands less visuospatial working memory capacity than in languages with this inversion. Linguistic comparison research remains necessary to confirm this hypothesis.

Raghubar et al. (2010) reviewed evidence indicating that the influence of the subcomponents of working memory on arithmetic performance might vary according to age. The visuospatial component is recruited in earlier phases of development, while children are still learning basic mathematical concepts, whereas the phonological loop is more relevant after these skills have already been mastered. Although Raghubar et al. (2010) did not specifically discuss number transcoding, this study reviews evidence regarding the complex and dynamic nature of the relationship between working memory and math achievement. Consistent with these results, no effect of visuospatial working memory on number transcoding was observed in second- to fourth-grade children in the present study.

The relationship between verbal working memory and phonemic awareness

The first step of writing Arabic numbers from dictation proposed by the ADAPT model (Barrouillet et al., 2004) is the phonological encoding of the auditory input, which consists of verbal numerals. Nevertheless, the procedures involved in this phonological encoding are still not completely specified. Here we showed that, in addition to working memory capacity, phonemic awareness also plays an important role in number transcoding. Our results showed that even when considering the influence of working memory and basic numerical skills on number transcoding, the predictive value of phonemic awareness abilities was substantial. This suggests that phonemic awareness is an important facilitator of the phonological encoding required in the initial steps of number transcoding.

Another aim of the present study was to clarify the influence of phonemic awareness on number transcoding. We aimed to investigate whether there is a direct influence of verbal working memory on number transcoding or if this association would be mediated by phonemic awareness. Our results presented evidence showing that phonemic awareness mediates the influence of verbal working memory in number transcoding, even after controlling for the effects of age and intelligence. In the path analyses, the removal of the Phoneme Elision-mediation path had a deleterious effect on model fit, which suggests that this parameter contributes crucially to improve the model fit.

This finding is consistent with the ADAPT model, which postulates that the first step in number transcoding would be the encoding of the verbal string into its phonological form (Barrouillet et al., 2004). This encoding phase would be followed by parsing procedures that segment these strings into smaller units. Smaller units are then sequentially processed through a production system in which verbal working memory is required for transcoding algorithms. It is possible to hypothesize that phonemic awareness would be the main cognitive precursor engaged in the phonological encoding phase that pre-cedes further verbal working memory involvement in number transcoding.

A plausible explanation for the association between phone-mic awareness and the influence of verbal working memory in number transcoding is the “weak phonological representation hypothesis” (Simmons and Singleton, 2008). According to this model, phonological processing deficits would impair the quality of phonological representations and thus affect aspects of numerical cognition that involve the manipulation of a verbal code.

The performance in verbal working memory and phonemic awareness depend on the same underlying and latent phonological representations (Hecht et al., 2001; Alloway et al., 2005; Durand et al., 2005). In our study, it was also possible to observe this association through the positive correlation between verbal working memory and phonemic awareness. Baddeley et al. (1975) had already suggested that, given that verbal short-term memory is a speech-based system, its capacity should be measured in more basic speech units, such as phonemes. Oakhill and Kyle (2000) also found that phonemic awareness (operationalized by means of phoneme elision and phoneme segmentation tasks) had a strong association with word and sentence span.

Evidence indicates that the influences of phonemic aware-ness and verbal working memory on literacy acquisition are both shared and unique (Mann and Liberman, 1984; Alloway et al., 2005). Factor analytical studies indicate that different types of phonological awareness tasks are loaded onto a single latent construct (Schatschneider et al., 1999). Tasks vary, however, in the additional cognitive demands they impose, regarding, for instance, working memory and other general cognitive components. According to this type of reasoning, different phonemic awareness tasks assess a common phonological processing construct plus additional varying components that change according to task demands. A task such as phoneme elision would consist then of at least two components, one tapping the phonological latent construct and the other one depending on working memory demands. Previous studies (Oakhill and Kyle, 2000; Alloway et al., 2005) have investigated the influence of verbal working memory on phonemic awareness performance. This question, however, is rather complex and our results emphasize the importance of also investigating the other direction of this relationship. This is especially relevant regarding the interplay between verbal working memory, phonemic awareness and number transcoding skills.

Another dimension adding complexity to the relationship between phonemic awareness and verbal working memory is the child's individual level of development, which may be characterized as the degree of automatization in phonological processing. Before the child acquires expertise with phonemic awareness, a task such as phoneme elision may impose heavy demands on the central executive. As the child progressively acquires experience with phonological processing, this task can be solved in a more automatic way, freeing working memory resources for other tasks relevant for more advanced operations. If, however, the child does not acquire abilities of accurately and automatically processing the phonemic units, precious working memory resources will be less available for numerical transcoding. Accurate and automatic phonemic processing liberates sparse processing resources necessary to solve more complex tasks.

Disclosing a complex relationship among working memory, phonemic awareness and transcoding has important consequences for math achievement in general and for its disorders. School achievement in reading and/or mathematics depends on a complex interaction between general and specific cognitive factors. As the child acquires expertise in specific domains, such as phonemic and/or quantitative representations, processing resources are liberated to work in increasingly more complex activities. The accurate and automatic nature of more basic sound and quantitative representations may thus influence the whole process of school learning, explaining variances both in achievement and in working memory. Johnson (2012) recently proposed that the occurrence of learning disabilities depends on such an interaction between specific and general cognitive factors. If a specific impairment, say in phonological or number processing, can be compensated by central executive resources, there is a smaller probability that the individual develops a learning disability. Otherwise, if executive processing resources are not sufficient to compensate or automatize basic cognitive processes, difficulties persist. This hypothesis has been explored in another report, investigating two cases of math learning difficulties (Haase et al., in press, this issue). In one case, math learning difficulties were associated with a lack of automatization and in the other case with impaired executive working memory resources.

There have been few studies that directly addressed the relationship between verbal memory and phonemic awareness during the performance of arithmetic tasks. Leather and Henry (1994) claim that both constructs share a certain amount of variance with arithmetic performance because phonemic manipulation demands arithmetical processes (for instance, phoneme elision tasks require, literally, the subtraction of a sound) and also involve working memory for the mental retention and management of verbal information. Phoneme elision tasks require both storage and processing of phoneme units because children usually hold the word in mind while deleting one sound and producing the new word with what is left (Oakhill and Kyle, 2000). Hecht et al. (2001) longitudinally investigated the role of phonological aware-ness in arithmetic development of children from different age ranges and found that from the 3rd to 4th grades, as well as from the 4th to 5th grades, this was the only subcomponent of phonological processing that explained the growth of performance in a standardized arithmetic task. According to the authors, the same memory resources engaged in arithmetic problem solving are also recruited in phonological awareness tasks.

Our findings are in accordance to what was reported by Michalczyk et al. (2013). The authors also found that the simultaneous inclusion of verbal and visuospatial working memory, the central executive as well as phonological awareness in a regression model showed that only phonological awareness—none of the working memory subcapacities—had a direct impact on basic quantity-number competencies. In this study, they investigated the performance of children aged 5 and 6 in a number sequence task, in which children had to recite the number word sequence forwards up to 31 and backwards from 5. Afterwards they had to name 3 subsequent and 3 preceding number words. Even though they did not use a transcoding task, one can infer from this result that phonological awareness might mediate the relation between verbal working memory and number words knowledge. Nevertheless, as mentioned above, our study was the first one to provide evidence regarding the mediation of the effect of verbal working memory on number transcoding by phonemic awareness.

Final remarks

Mathematics encompasses a range of several different competences, such as numerical estimation, word problems, fact retrieval and number transcoding. Standardized arithmetic tasks usually assess these different abilities simultaneously and do not tap their specificities. It is important to investigate the distinct cognitive mechanisms that are associated with each of these mathematical skills. In our study, we concluded that phonemic awareness and verbal memory are directly connected to number transcoding, being important pathways between the verbal input and the transcription of the Arabic output.

The acuity of number sense, as measured by the Weber Fraction, did not influence number writing, suggesting that the assessment of numerical magnitude is not a necessary step in number transcoding. The acuity of number sense has been considered an important predictor of arithmetic performance (Halberda et al., 2008), but its relationship to number transcoding is less explored.

Although we did not explicitly assess children with learning disabilities, our results provide additional support to the hypothesis that phonemic awareness might be a cognitive mechanism that underlies both dyslexia and dyscalculia. Epidemiological studies describe high comorbidity rates between reading and mathematical difficulties: approximately 40% of dyslexics also have arithmetical difficulties (Lewis et al., 1994), and the prevalence of dyslexia and dyscalculia is similar, approximately 4–7% (Dirks et al., 2008; Landerl and Moll, 2010). The finding that phone-mic awareness is related to number transcoding is useful in the comprehension of mathematical difficulties presented by dyslexic children (Haase et al., in press, this issue). We suggest that this should also be assessed in neuropsychological evaluations as well as in clinical interventions for children with learning disabilities.

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CHAPTER 3

SYMBOLIC AND NONSYMBOLIC REPRESENTATIONS OF NUMBER IN ADULTS.

STUDY 4: EFFECTS OF LITERACY ON SYMBOLIC AND NONSYMBOLIC REPRESENTATIONS OF NUMBERS.

Unpublished manuscript

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Abstract:

In the present study we investigated the influence of educational factors on symbolic and nonsymbolic representations of number by means of a number transcoding and magnitude comparison task. In view of that, we assessed a sample of semi-illiterate adults and two control samples of literate adults and school age children. Results revealed that education interferes in symbolic representations of number, mainly in the syntactic mechanisms of the Arabic code, but not on nonsymbolic representations, indexed here by the Weber fraction.

INTRODUCTION

Research on the development of numerical abilities has gained considerable attention over the last decades. Significant advances have been observed in the knowledge regarding the different cognitive functions and brain structures involved in the development of the large variety of basic numerical abilities (Dehaene & Cohen, 1995; Dehaene, Piazza, Pinel, & Cohen, 2003). It is assumed that the basic numerical skills are grounded on both ancient evolutionary and culturally acquired mechanisms. It is thought that the processing of nonsymbolic numerical magnitudes (sets of concrete items) is subserved by analogous brain circuitry in both animals and humans (Nieder & Dehaene, 2009). It is also argued that these nonsymbolic representations constitute the starting point for the development of the more recent culturally-acquired mechanisms, such as the symbolic systems, arithmetics, among others (Piazza, 2010).

Despite the importance attributed to the development of numerical processing mechanisms, little is known about the acquisition of basic numerical abilities in individuals with no or little access to education. Some evidence suggests that illiterates and semi-illiterates participants are able to perform basic numerical processing tasks, such as two-digit number comparison (Wood, Nuerk, Freitas, Freitas, & Willmes, 2006) and even some basic calculations (Deloche, Souza, Willadino-Braga, & Dellatolas, 1999). Nevertheless, little is known about the nature of these representations on individuals with low literacy.

In the present study, we investigated the influence of educational factors on symbolic and nonsymbolic processing of numbers. To address the impact of literacy on nonsymbolic representations, we acquired psychophysical measures of Approximate Number System (ANS) acuity in adult individuals with very low literacy, and in literate adults. One model suggests that the ANS is an inherited pre-verbal system that represents numbers in an approximate and logarithmically compressed fashion, according to the classical psychophysical laws of Weber and Fechner (Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004). Not only the basic numerical abilities, but the whole symbolic numerical thinking, are thought to be grounded on the ANS. Previous studies in indigenous populations with a very reduced lexicon of verbal numbers suggest that the more one is educated in a language with an expanded numerical lexicon, the higher is the accuracy levels observed in ANS measures (Pica, Lemer, Izard, & Dehaene, 2004; Piazza, Pica, Izard, Spelke, & Dehaene, 2013). Therefore, the education, or more specifically, the access to a complex symbolic system for numbers, would have a feedback effect on nonsymbolic representations, refining its accuracy and thus, allowing more precise numerosity estimations and discrimination. Conflict results were reported by Butterworth, Reeve, Reynolds and Lloyd (2008), who investigated basic numerical skills in children speakers of two Australian languages with restricted numerical lexicon. They reported that language does not influence the acquisition of numerical concepts, such as counting. Nevertheless, results are not directly comparable, since the focus was on different aspects of numerical representations.

Zebian and Ansari (2012) investigated illiterate adults and showed that educational factors may have an influence only in the symbolic representations of number. Nevertheless, they investigated symbolic and nonsymbolic processing by means of simple comparison tasks, using only very small magnitudes, what could have masked possible effects on nonsymbolic representations. Therefore, this is not a resolved issue, and the effect of education on nonsymbolic representations reported in previous studies may have been confounded by cultural variables and by task characteristics. In this sense, we hypothesized that if ANS acuity is influenced by educational factors, individuals with higher literacy should present more refined ANS accuracy. By studying adults with low literacy levels, we can simultaneously control the effects of age, education and culture (access to a complex number-word system) on the acuity of the ANS.

Concerning symbolic representations of numbers, one important aspect of numerical processing that still deserves attention is what illiterates know about transcoding between different symbolic numerical notations and about the underlying lexical and syntactic mechanisms of the verbal and Arabic (place-value) number system. To our knowledge there is no previous investigation if this topic. In the present study, we addressed this issue by investigating the performance of illiterates with up to 4 years of formal education in a number of transcoding tasks.

In order to address the impact of literacy on symbolic representations, we investigated the understanding of the Arabic (place-value) notation in adults with low literacy by means of a number transcoding task. Here, the use of such a task is of major relevance since, in contrast to nonsymbolic or single-digit comparison tasks, it constitutes a purely culturally transmitted skill acquired by means of deliberate learning and teaching.

To investigate symbolic numerical representations, we will compare number transcoding performance of adults with low literacy with that of children attending from 1st to 4th grades of elementary school. These children were assessed in the context of another study of numerical abilities of children with and without mathematics difficulties (Moura et al., 2013; Moura et al., *submitted*).

We expect that education may interfere in number transcoding in several ways. First, the acquisition of reading and writing skills has a reciprocal relationship with the improvement of phonemic awareness (Castles & Coltheart, 2004). According to the ADAPT model (Barrouillet, Camos, Perruchet, & Seron, 2004) and to empirical data, phonemic awareness also plays a decisive role in number writing, acting as a mediator of the influence of working memory on number transcoding (Lopes-Silva, Moura, Julio-Costa, Haase, & Wood, 2014). Despite some evidences suggest that rudimentary aspects of the Arabic number syntax can be acquired by children even before formal teaching (Barrouillet, Thevenot, & Fayol, 2010), here we expect that number transcoding will impose significant difficulties for semi-illiterate adults, specially due to the comprehension of syntactic mechanisms.

Second, it can also be argued that the positive effect of education on nonsymbolic numerical representations may have an effect on number transcoding performance.

According to semantic models of number transcoding, the conversion between numerical input and output is mediated by a semantic representation of numerical magnitude (McCloskey, Caramazza, & Basili, 1985; McCloskey, 1992). In view of that, we will investigate the influence of ANS acuity on number transcoding. In case ANS has an effect on number transcoding performance, we can hypothesise that there is, indeed, a semantic mediation between numerical inputs and outputs. If this influence is not present in our data, we can assert that quantitative numerical semantics, as measured by ANS acuity, has no influence in number transcoding.

Additionally, we will investigate the effect of general cognitive abilities on number transcoding performance. As argued by the ADAPT model (Barrouillet et al., 2004), and consistently confirmed by empirical findings (Camos, 2008; Moura et al., 2013; Zuber, Pixner, Moeller, & Nuerk, 2009), working memory capacity plays a decisive role in number transcoding and, thus, will be addressed here. We also acquired measures of intelligence, since it is a powerful predictor of academic success and thus, can be an important confound variable in the study of individuals with very low educational levels (Strenze, 2007).

METHODS

Participants

Three groups of participants were assessed in the present study. The semi-illiterate group (SIL) consisted of 26 participants (19 female) with ages ranging from 27 to 55 years (mean = 45.9 years, sd = 7.9 years). All participants were born in Brazil, and were recruited in the first grade of alphabetization courses for adults in the city of Belo Horizonte. These courses occur in the late afternoon, and are coordinated by the city administration, focusing on the training of basic reading and writing skills. In order to take part in this study, participants from these courses needed to be between 18 and 55 years-old, and have no more than 4 years of formal schooling. Despite the very low level of schooling, all semi-illiterates were socially functional and engaged in formal jobs, as shown in the Table 1. The average literacy (AL) group was composed of adults (n = 10) with ages ranging from 22 to 54 years (mean =

39.6 years, sd = 12.3 years), and who become literate at the regular ages. To avoid comparing subjects with very discrepant socioeconomic backgrounds, participants of the AL group were recruited in educational courses for adults who stopped studying before concluding high school at the expected ages.

Table 1
Socio-demographic characteristics of the semi-illiterate sample.

Participant	**Gender**	**Age (years)**	**Profession**	**Life-long education**
V.C.S	female	38	Housewife	3
G.D.S	female	48	Cook	3
E.S.V.	female	27	Housewife	1
D.A.B	male	39	Door-keeper	4
Z.F.S	female	54	Housemaid	3
A.G.S.	female	47	Housemaid	4
E.R.S.	female	35	Hairdresser	4
E.A.F.	female	36	Housemaid	3
L.M.C.	female	51	Housemaid	2
J.H.D.	male	37	Door-keeper	4
M.A.	female	50	Housemaid	4
A.M.L.	male	54	Door-keeper	3
M.N.S.N	female	49	Housemaid	1
L.C.B.M.	female	55	Housemaid	4
V.M.S.	female	59	Housemaid	4
L.D.A.	female	54	Housemaid	3
N.M.P.	female	48	Caregiver	4
R.D.G.	male	37	Construction worker	1
M.I.F.	female	51	Housemaid	3
M.A.A.	female	48	Caregiver	4
A.J.A.	male	40	Construction worker	4
J.E.P.S.	male	49	Door-keeper	2
M.F.C.S.	female	55	Housemaid	3
D.A.S.	male	43	Construction worker	1
M.A.P.N.	female	47	Caregiver	2
M.L.G.S.	female	48	Housemaid	2

Furthermore, in order to classify in more detail the level of competence the SIL group had in the Arabic number writing task, we used a data-set of 985 Brazilian children of a previous study of ours (Moura, Lopes-Silva, Vieira, Paiva, Prado, Wood & Haase, *submitted*), which comprised children attending from 1st to 4th grades of elementary school. These children were recruited in both public and private schools in the cities of Belo Horizonte and Mariana, and were collectively assessed with measures of school achievement and with a number transcoding task. The option to include school children in this study is to have enough variability in transcoding scores, as number writing and reading tasks are far too easy for control adults. Moreover, the data from school children allow us to classify in deeper detail the level of transcoding difficulties in adults with low education.

Procedure

Participants were assessed in quiet rooms in the schools during one session of approximately one and a half hour. The various tasks were presented in pseudo-random orders. The study was approved by the local research ethics committee (COEP–UFMG). The experimenter explained the research purposes orally in front of a witness and participation occurred only after informed consent was obtained.

Intelligence assessment

Wechsler Adult Intelligence Scale

Since low literacy may have a negative impact on IQ measures (Ramsden, Richardson, Josse, Shakeshaft, Seghier, & Price, 2013), we used the Brazilian version of the Wechsler Adult Intelligence Scale (WAIS-III; Nascimento, 2000) to ensure that intelligence levels in our sample are inside the normal range. Due to time constraints in data collection, we opted to use a shorter form of the test, with the Vocabulary and Block Design subtests, which are commonly used to estimate verbal and performance IQ's. There is no validation of shorter forms of the WAIS-III for Brazilian samples, and thus we will restrain our analysis to the scaled scores.

Working memory assessment

Digit Span Task

The backward Digit Span task was used to assess the verbal component of working memory, following the procedures of the Brazilian version of the Wechsler Adult Intelligence Scale (Nascimento, 2000).

Corsi Block Tapping Task

The backward order of the Corsi Block task was administered as a measure of the visuospatial component of working memory (Kessels, van Zandvoort, Postma, Kapelle & de Haan, 2000)

Literacy assessment

Word and Pseudoword reading task

Participants read a list of 40 real words selected according to their regularity, length, frequency and lexicality, and 20 pseudowords developed for assessing reading skills of students until the seventh year of schooling (SaIles, Piccolo, Zamo, & Toazza, 2014). Half of the real word list was composed by regular words, and the other half by irregular words, all matched by length and frequency.

Numerical skills assessment

Nonsymbolic comparison task

In this task participants were instructed to compare two sets of dots indicating the larger one the fastest they could. The paradigm was designed following the same parameters used by Piazza et al. (2013), using the software Presentation® (Neurobehavioral Systems, Albany, CA, http://www.neurobs.com), in conventional laptops. Stimuli consisted of black dots displayed in separated white circles on each side of the screen. In each of the 160 trials, one of the two arrays contained either 16 or 32 dots. This array (hereafter *n*1) is defined as the reference number to which the other array must be compared. The other array (hereafter *n*2) contained 10, 12, 14, 15, 17, 18, 19 or 22 dots when *n*1 was 16, and 20, 24, 28, 30, 34, 36, 38 or 44 dots when *n*1 was 32. In such a way, the ratio between the larger and the smaller arrays was kept the same (0.625, 0.750, 0.813, 0.875, 0.938, 0.941, 0.889, 0.842, 0.800 and 0.727) regardless of *n*1's magnitude. Stimuli remained on-screen for a maximum of 5000ms, or until participants gave their response. All responses were captured by pressing the leftmost or the rightmost buttons of the keyboard, depending on the side of the array identified by the participant as "larger". Response sides were contrabalanced so that in half of the trials the larger set was on the left side of the screen. Each testing trial was preceded by a fixation mark with fixed duration of 1000ms, and followed by an inter-trial interval of fixed 500ms.

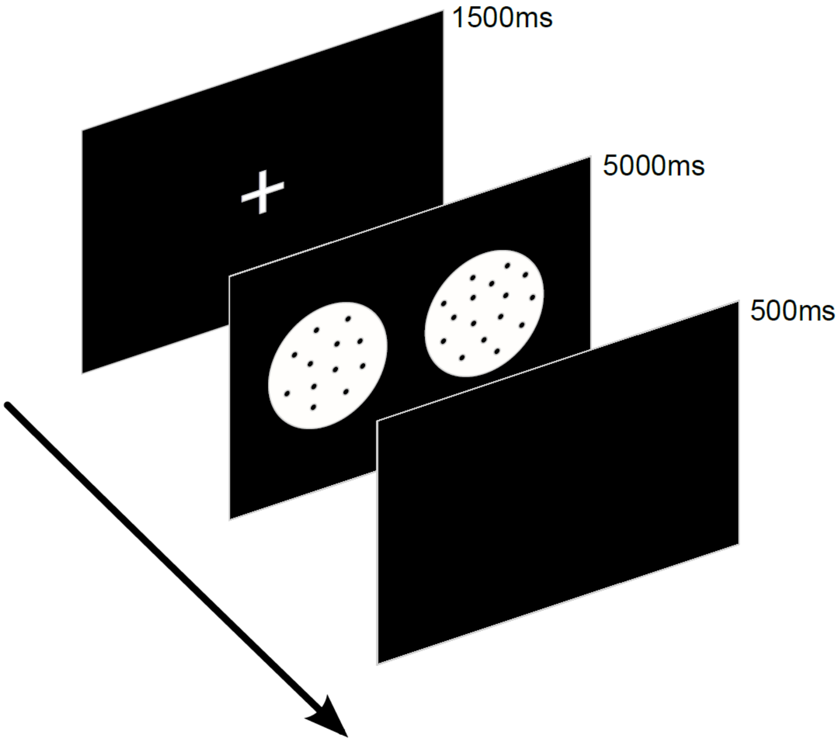

Figure 1 – Nonsymbolic comparison task.

The internal Weber fraction (hereafter *w*) was used as an index of ANS acuity. It was calculated for each participant based on Dehaene's log-Gaussian model (Dehaene, 2007) by fitting the psychometrics curves for both *n*2 references with a single sigmoid function of the log *n*1/*n*2 ratio, using the methods described by Piazza *et* al. (2004) and Piazza *et* al. (2013). In a nutshell, w is a measure derived from error rates in each n1/n2 ratio, being calculated individually for each participant using the formula 1, where *erfc*(x) is the complementary error function. W is a measure of the internal variability (also referred as "noise" or standard deviation) in the internal representation of numerosity, so that larger values indicates a less precise representation.

$$\frac{1}{2}\operatorname{erfc}\left(\frac{n_1 - n_2}{\sqrt{2}w\sqrt{n_1^2 + n_2^2}}\right)$$

Formula 1 – Complementary error function for the calculation of *w* scores.

Arabic number writing task

The Arabic Number Writing Task is an expanded version of a previous task used to assess basic numerical abilities in children (Haase, Júlio-Costa, Lopes-Silva, Starling-Alves, Antunes, Pinheiro-Chagas, & Wood, 2014; Lopes-Silva, Moura, Júlio-Costa, Haase, & Wood, 2014; Moura, Wood, Pinheiro-Chagas, Lonnemann, Krinzinger, Willmes, & Haase, 2013). In this version, a total of 81 one- to four-digit numbers were dictated in a fixed order. The item set comprised 2 one-digit numbers, 6 two-digit numbers, 19 three-digit numbers and 54 four-digit numbers. We used the number of rules required for transcoding as an index of numerical complexity. According to the ADAPT model, the numbers presented in this task required from 2 to 7 different rules in order to be correctly transcoded. To avoid errors due to the forgetting of the verbal dictated forms, numbers were repeated one more time in case a participant asked for it.

RESULTS

Intelligence

We used the arithmetical mean of the scaled scores in the Vocabulary and Block Design subtests as an index of general intelligence. As expected, individuals from the SIL group showed lower intelligence levels, with a mean value of 7.2 (sd = 0.787) against a mean of 10.6 (sd = 2.29) of the AL group ($t[10.04] = 4.56$, $p < 0.001$). The lowest value observed in the two samples was 6, what corresponds to 1.3 standard deviations below the mean (according to the manual's norms). Therefore, we assumed that, despite the lower intelligence, all participants of the SIL group have normal intelligence. The average of the scaled scores was entered as covariate in further analyses.

Word and Pseudoword reading task

As expected, accuracy in the word and pseudoword reading task was significantly lower ($t[25.41] = 9.17$, $p < 0.001$) for the participants of the SIL group (mean 48.7%, range: 0% - 95%) than for the participants of the AL group (mean 96.8%, range: 91% - 100%). According to the task's norms, 12 participants of the SL group showed a performance below the 50th percentile of children who did not complete the first year of education, therefore, confirming almost complete illiteracy in these participants. Other 12 participants of this group showed a performance below the 50th percentile of children in the 2nd year of education, and one participant showed a performance compatible with the 50th percentile of the 3rd school year.

Nonsymbolic comparison task

Data of the nonsymbolic comparison task were trimmed for each participant in order to exclude trials with reaction times exceeding 3 standard deviations from individual means. Following this criteria, less than 1% of total trials ($n = 21$) had to be excluded from the analyses. Additionally, less than 1% of the trials ($n = 21$) had to be excluded because of non-responses. Mean accuracy rate was high for both SIL (82% of hits, ranging from 72% to 94%) and AL groups (81% of hits, ranging from 71% to 90%). As shown in Figure 1, "larger" responses of AL and SIL groups at each $n2$ value obeyed the Weber-Fechner law, that is, showed sigmoidal distributions when plotted in a linear scale (Figure 2a), and sigmoidal distributions with identical slopes when plotted in a log scale (Figure 2b).

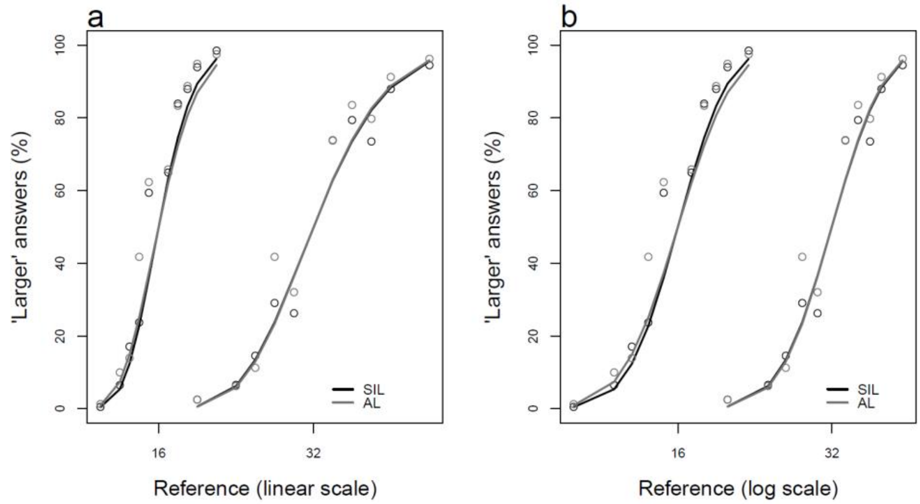

Figure 2 – Results of the nonsymbolic comparison task.

In accordance with the Weber's law, we observed a clear improvement in performance as the ratio between n1 and n2 increased (that is, occurrence of 'larger' responses decreased steadily as n1 got smaller than n2, and increased as it got larger than n2). Moreover, the fitting values (R squared) of both groups were high (SIL: mean = 0.96, range: 0.86 - 0.99; AL: mean = 0.95, range: 0.91 - 0.99), suggesting a high agreement between the psychophysical model and the behavioral data. One participant from the SIL group was excluded from the study because the regression fit was not satisfactory. Importantly, *w* values were similar in the two groups investigated here, with average values of 0.19 for SIL participants and 0.20 for AL participants. An independent-samples t-test confirmed the equality of these values (t[15.3] = 0.49; *p* = 0.634).

As depicted in Figure 3, large individual differences were evident in nonsymbolic representations of both SIL and AL groups, with *w* values of all participants ranging from 0.07 to 0.34 (0.07 to 0.30 in the SIL group, and 0.11 to 0.34 in the AL group). An investigation of w distributions in the two samples, by means of Kolmogorov-Smirnov tests, confirmed that *w* values are normally distributed (AL: D = 0.181, *p* = 0.47; SIL: D = 0.135, *p* = 0.28).

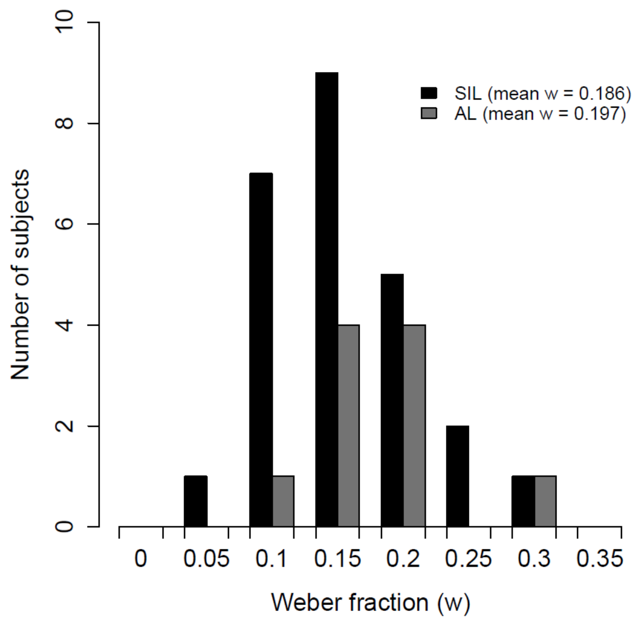

Figure 3 – Distribution of *w* values over the AL and SIL groups.

Due to the high variability in the reading capacity within the SIL group, we ran a linear regression with *w* as the dependent variable and reading accuracy as the independent variable, including only SIL individuals. The model (F = 3.28, p = 0.08) showed that reading skills (our index of literacy) has no significant influence on *w* scores (Figure 4).

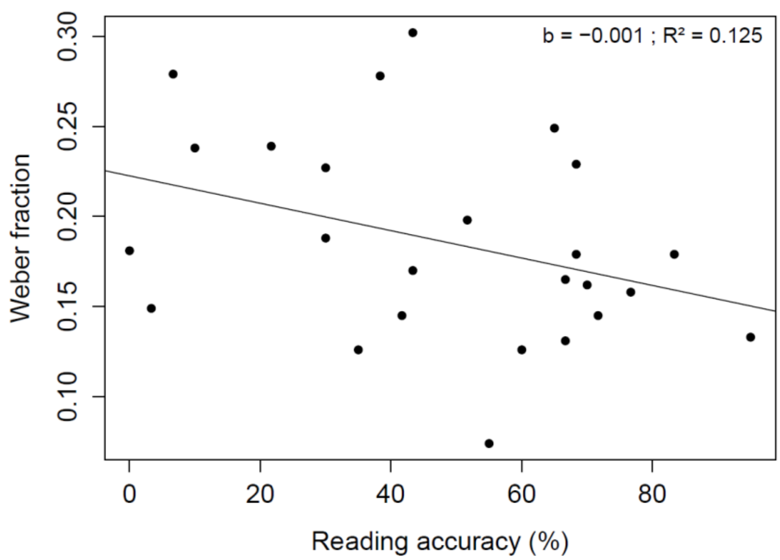

Figure 4 – Regression model of w values and reading achievement.

Arabic number writing task

As expected, performance in the Arabic number writing task was remarkably different between the two adult groups. AL participants completed the task almost flawlessly, with an average error rate of modest 1%. Therefore, this group will not be included in further analysis. In turn, the SIL group showed in average 51% of wrong answers, varying from 2% to 83%.

Performance of SIL participants was highly influenced by the syntactic complexity of the numerals. Error rates increased from 5% in numbers that require only 2 different rules in order to be transcoded, to 67% in numbers requiring 7 different rules (Figure 5). An ANOVA was performed comparing the error rates in each complexity level (number of rules). Working memory measures were entered as covariates in order to rule out the possibility that the increase in error rates with syntactic complexity was attributable, solely, to an increase in the demand on working memory resources in the more difficult items.

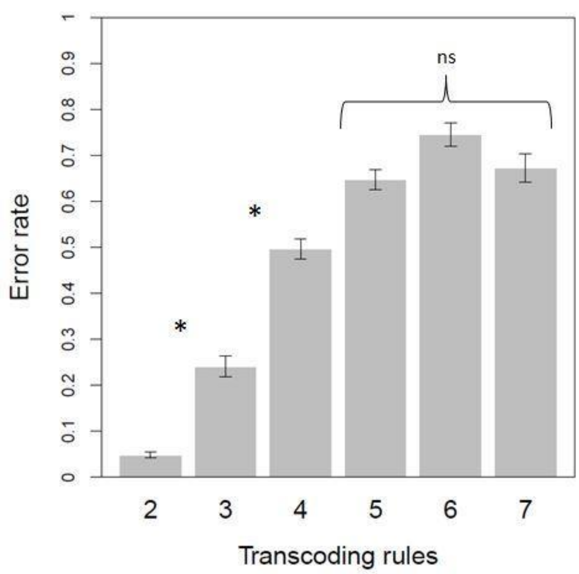

Figure 5 – Number transcoding performance according to the quantity of transcoding rules.

Results disclosed a main effect of syntactic complexity, as error rates increased significantly with the quantity of transcoding rules required (F[5] = 9.26, MSE 0.67; p < 0.001, η_p^2 = 0.30).

Furthermore, this effect could not be attributable to differences on the demand of working memory resources, as syntactic complexity did not interact neither with digit span (F[5] = 2.70, MSE = 0.19, p = 0.07, η_p^2 = 0.11) nor with Corsi span (F[5] = 1.65, MSE = 0.11, p = 0.20, η_p^2 = 0.07). Nevertheless, digit span showed a significant effect on general error rates in the Arabic number writing task (F[5] = 6.23, MSE = 0.28, p < 0.001, eta = 0.22), as predicted by most transcoding models.

Repeated contrasts were run in view to disentangle the main effect of syntactic complexity. Significant differences between numbers requiring 2 and 3 (F = 8.97, p < 0.01), and between numbers requiring 3 and 4 transcoding rules (F = 10.18, p < 0.01) were found. In turn, no significant differences were found between numbers that require 5, 6 or 7 transcoding rules.

Due to the low error rates observed in the AL group, further analysis will be conducted taking the sample of school-aged children as a comparison. Furthermore, with this procedure we will be able to classify the performance of SIL participants in the Arabic number writing task according to years of education. The sample of children performed a similar but shorter version of Arabic number writing task. Therefore, to make their results comparable, we grouped items in three levels of syntactic complexity: low complexity (less than 4 transcoding rules), moderate complexity (4 transcoding rules) and high complexity level (more than 4 transcoding rules). Results of both samples are depicted in Figure 6.

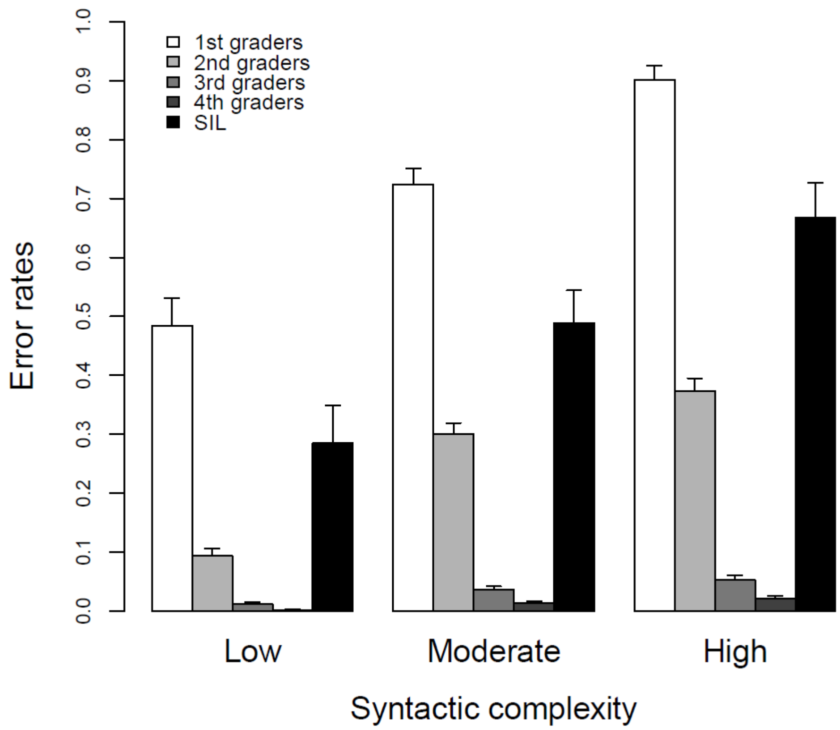

Figure 6 – Performance of school children and SIL group in the Arabic Number Writing Task, according to syntactic complexity.

A visual inspection of the Figure 6 suggests that the achievement of SIL participants in the Arabic number writing task is, in general, comparable to that observed in 1st and 2nd graders. To better characterize it, a 3x5 ANOVA was performed with syntactic complexity as within-subjects, and group as between-subjects factors. Results revealed a strong main effect of syntactic complexity ($F[2, 1612] = 299.04$, $MSE = 5.01$, $p < 0.001$, $\eta_p^2 = 0.27$). Repeated contrasts showed significant differences between all three levels of complexity (all p's < 0.001). Also, a significant main effect of group was observed ($F[1, 806] = 309.11$, $MSE = 7.57$, $p < 0.001$, $\eta_p^2 = 0.60$) and a significant interaction between these factors ($F[8, 1216] = 69.66$, $MSE = 32.38$, $p < 0.001$, $\eta_p^2 = 0.26$). Paired comparisons with Bonferroni correction showed that in all levels of syntactic complexity the only groups with similar performance were the children from 3rd and 4th grades (all p's > 0.05). Therefore, analyses in the next sections will not include these children.

Error Analysis

Next, an investigation of the erroneous responses was performed. Firstly, errors were classified in two broad categories of lexical and syntactic errors. Lexical errors occur when a lexical element in the number was substituted by another one (1500 written as 1300), while syntactic errors occurred when the lexical elements were misplaced in the syntactic frame (135 written as 153), or when this frame was wrongly generated (145 written as 100405).

The vast majority of erroneous responses (95%) were classified as syntactic, in accordance to what has already been reported for children and neurological cases (Deloche & Seron, 1982a, 1982b). This pattern was similar to what was observed in our group of children up to the 2nd grade (Figure 7). A 2x2 ANOVA was run on error rates with group as between subjects factor, and error class as within subjects factor. Results revealed a main effect of error class, with higher occurrence of syntactic over lexical errors ($F[1, 326] = 291.63$, $MSE = 32.38$, $p < 0.001$, $\eta_p^2 = 0.47$), and a main effect of group, as error rates were, in general, higher for the SL group ($F[2, 326] = 10.55$, $MSE = 0.89$, $p < 0.01$, $\eta_p^2 = 0.06$). Interestingly, a significant interaction between the two factors was also observed ($F[2, 326] = 8.71$, $MSE = 0.97$, $p < 0.001$, $\eta_p^2 = 0.05$).

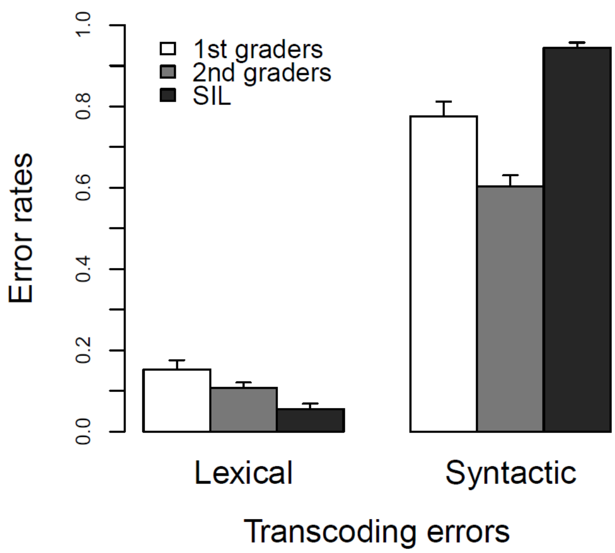

Figure 7 – Frequency of lexical and syntactic errors in school children and SIL group.

A deeper analysis of the syntactic errors was also performed in view of unfolding the source of these difficulties. According to the ADAPT model (Barrouillet et al., 2004), 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 did 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. Frequencies of these errors are depicted in Figure 8.

A 2X2 repeated measures ANOVA was performed on error rates, with error class (additive composition and wrong frame) as within-subjects factor, and group as between subjects factor. Results disclosed a main effect of group (F[2, 326] = 22.50, MSE = 1.75, $p < 0.001$, η_p^2 = 0.12), as participants of the SIL group showed overall higher error rates, and a main effect of error class (F[1, 326] = 21.10, MSE = 1.75 $p < 0.001$, η_p^2 = 0.06), due to higher frequencies of wrong frame errors. Nevertheless, the interaction between the two factors was not significant (F[2, 247] = 2.05, MSE = 0.17, $p = 0.06$, η_p^2 = 0.01), thus suggesting that the pattern of higher frequency of wrong frame over additive composition errors was similar in both groups.

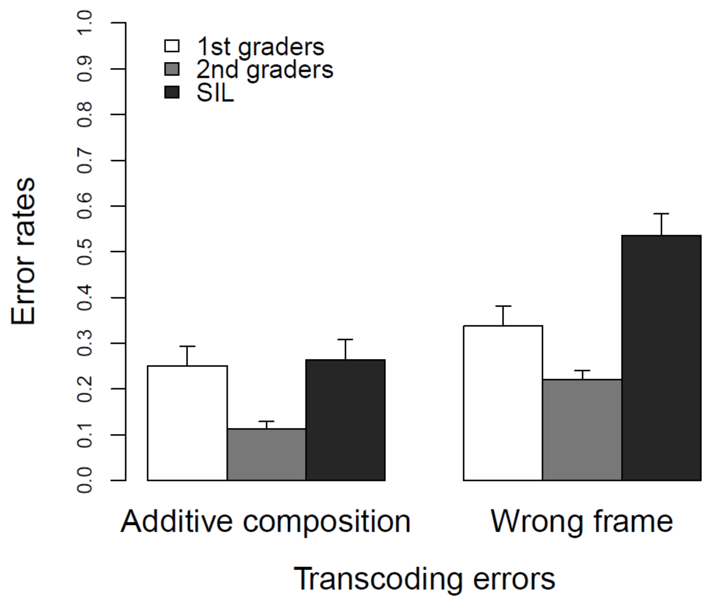

Figure 8 – Frequency of additive composition and wrong frame errors in school children and SIL group.

Finally, in view of investigating the contributions of specific cognitive factors on number transcoding, we ran a series of stepwise regression models using data from SIL participants only. All the models included as independent variables the verbal and visuospatial working memory components, the Vocabulary and Block Design subtests of the WAIS-III, w, and the score on the reading task. As dependent variables, we tested overall error rates on the Arabic Number Writing task, and the rates of lexical, syntactic, additive composition and wrong frame errors. Only two models yielded significant results. First, the overall error rate in the task was significantly predicted by the Digit Span task only ($F = 7.37$, $p = 0.01$, adjusted $R^2 = 0.21$). Secondly, wrong frame errors were significantly predicted by Digit Span and Corsi Span measures ($F = 6.30$, $p < 0.01$, adjusted $R^2 = 0.31$).

DISCUSSION

In the present study, we investigated the influence of education/literacy on nonsymbolic and symbolic representations of numbers. Two groups of adult participants, with similar socioeconomic status and intellectual skills, but presenting outstanding differences in literacy, were compared. Additionally, a sample of young children was also investigated. Our results revealed that, in one hand, semi-illiterate individuals fail in acquiring a complete knowledge of the syntax of Arabic numerals, but in the other hand, acuity of the ANS showed to be comparable to that of literate individuals. These results have several implications, which will be further discussed in the next sections.

ANS acuity

Concerning the relation between education and nonsymbolic representations, our data support the hypothesis that education and literacy have no significant effect on ANS acuity. We assessed the accuracy of literate and semi-illiterate individuals in discriminating a series of numerosities and quantified their precision at the individual level, adjusting classical psychophysical functions. We found that ANS acuity is normally distributed in both literate and semi-illiterate samples. This finding is in accordance to the study of Halberda, Mazzocco and Feigenson (2008), so that large individual differences in nonsymbolic abilities are observed in the population. Moreover, we extrapolated it by showing that ANS acuity is comparable in both samples investigated here, thus leading us to conclude that education, as measured by literacy, does not influence on nonsymbolic representations of number.

Number transcoding

Concerning the influence of education on number transcoding, in this study we addressed two main topics. First, we investigated the performance of semi-illiterates in a number transcoding task. According to our data, semi-illiterates showed severe difficulties in writing 3- and 4-digit numbers, in a performance comparable to that of children attending to 1st and 2nd grades. An analysis of erroneous responses revealed the nature of these difficulties. In general, the large majority of errors committed by semi-illiterate individuals was due to syntactic mechanisms, and only a few errors could be attributed to lexical mechanisms, a pattern similar to what is commonly observed in young children (Camos, 2008; Moura et al., 2013; Zuber et al., 2009).

Interestingly, our analysis also showed that the ratio between syntactic and lexical mistakes is significantly higher in semi-illiterate adults, who committed more syntactic errors and less lexical errors than school children. Regarding the very low occurrence of lexical mistakes, we can infer that semi-illiterate adults can benefit from daily experience and expand their numerical lexicon. The nature of syntactic errors reflected what was already observed in young children, that is, were mainly due to the lack of necessary transcoding rules. Therefore, contrary to the development of a numerical lexicon, we can infer that formal teaching has a pivotal role in improving the knowledge of the numerical syntax.

Second, our results can also help to clarify the discussion about the semantic route in number transcoding. Since the elaboration of the McCloskey's semantic model (1992; McCloskey, Caramazza, & Basili, 1985) there is a debate how many routes are there and the nature of the number transcoding routes (Cipolotti, 1995; Van Loosbroek, Dirkx, Hulstijn, & Janssen, 2009). Recently, some authors have argued in favor of the existence of a semantic route, in which numbers are transcoded by accessing their quantitative numerical magnitudes (Imbo, Bulcke, Brawer, & Fias, 2014; Van Loosbroek, Dirkx, Hulstijn, & Janssen, 2009). Here we showed that an intact representation of numerical magnitudes has no influence on number transcoding performance. Therefore, we conclude that a semantic route, at least in terms of an access to approximate magnitudes as represented in the mental number line, cannot account for number transcoding performance.

Education and the numerical representations

In general, our data shows that education has an influence only on numerical representations that require the use of symbolic systems. It is important to note, however, that comparisons with previous research must be made carefully. The hypothesis of an education-driven enhancement of nonsymbolic representations (ANS acuity) has been put forward based on data of individuals raised in isolated cultures, whose number word system possess a very limited lexicon for numbers (Piazza et al., 2013). Contrary to these indigenous populations, semi-illiterate individuals are immersed in an industrialized and numerate society, with normal access to a complex number word system. As shown here, semi-illiterates do not have important difficulties in the acquisition of a complete numerical lexicon but with the numerical syntax of larger numbers (3- and 4-digit numbers). In turn, such indigenous populations still lack a complete numerical lexicon.

Together with the study of Piazza et al. (2013), who showed that the learning of Portuguese number words by indigenous individuals enhances the ANS acuity, we can argue that literacy is a sufficient condition for the improvement of nonsymbolic representations of number, while the access to a number word system with an expanded numerical lexicon is a necessary condition. Therefore, future studies must try to disentangle the relation between the improvement of ANS acuity and the acquisition of a numerical lexicon in children.

Conclusion

In conclusion, the present study provides evidence that literacy influences symbolic representations of numbers in the sense that it is indispensable for the comprehension of the numerical syntax. Nonsymbolic representations and the acquisition of the numerical lexicon, in turn, may be more influenced by culture and the access to a number word system with expanded lexicon.

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CHAPTER 4

Concluding remarks.

GENERAL CONCLUSION

The present thesis addressed three broad questions about number transcoding abilities: how can it be used as a tool for neuropsychological assessment, how it is influenced by the level of arithmetics abilities, and how is it related to other cognitive functions, such as working memory and phonological processing.

In study 1 the basic psychometric properties of an Arabic number writing task were investigated. We showed that, besides being simple and rather fast to administer, the task is a powerful tool for screening mathematics difficulties in young children (early elementary school, more specifically).

In study 2 Arabic number writing and reading skills of children with different profiles of mathematics achievement were assessed. Although we confirmed previous studies on the pivotal role of working memory skills in number transcoding, we showed that working memory capacity cannot fully account the difficulties exhibited by children with mathematics difficulties in writing and reading Arabic numerals. Importantly, we showed a clear developmental lag in the acquisition of a basic numerical lexicon and in mastering the place-value syntax was observed in children with mathematics difficulties.

In study 3 the influence of phonological abilities on number transcoding was investigated. Even though these abilities occupy a relevant place in the ADAPT model, no study so far had investigated the influence of such ability in children's performance. We found that phonemic awareness significantly affected children's performance on number transcoding. Furthermore, we showed that phonemic awareness acts as a mediator of the influence of verbal working memory in number transcoding.

The last study investigated symbolic and nonsymbolic representations of numbers in adults with low literacy by means of number transcoding and magnitude comparison tasks. We found that, like children attending to first and second grades, semi-illiterate adults still struggles to transcode 3- and 4-digit numbers, mainly due to the lack of transcoding rules. Interestingly, the numerical lexicon showed to be acquired despite of the low education. In turn, nonsymbolic representations, indexed by the ANS accuracy, were similar to that observed in literate adults, thus suggesting that education does not affect the development of this representation.

Together, the four studies provide several contributions to the literature of numerical cognition. We described in detail the development of number transcoding abilities in school children and we showed, for the first time, how it is related to mathematics achievement. Besides theoretical implications, this finding has a more immediate practical application, once it can be used in the educational context as both screening and remediation of mathematics difficulties. It was also shown that, besides being a rather easy task to learn, number transcoding difficulties may persist until adulthood if not properly addressed.

Other important contribution of the studies concerns the theoretical models of number transcoding. Here we confirmed and extended previous findings supporting number transcoding as an asemantic, rule-based process. The pivotal role of working memory in number transcoding was confirmed and, in the context of mathematics difficulties, was specified. Furthermore, the effect of phonological abilities in number transcoding was studied for the first time.