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Reading and writing words and numbers: Similarities, differences, and implications

1 Introduction

Literacy and numeracy are culturally acquired abilities that are well established as crucial for educational and vocational prospects (Parsons & Bynner, 1997; Ritchie & Bates, 2013; Romano et al., 2010). When investigating these abilities in children, researchers from educational and cognitive sciences often focus on the writing and reading of either words or numbers. Accordingly, these usually represent two independent lines of research. Nevertheless, in recent years there is increasing research interest into relevant commonalities between learning to read and write words as well as numbers (e.g., Lopes-Silva et al., 2016).

It has been argued that efficient processing of words and numbers requires a partially overlapping cognitive architecture including basic perceptual abilities, attention, working memory (WM), verbal, visuo-spatial and visuo-constructional processing as well as graphomotor sequencing, among others (e.g., Collins & Laski, 2019; Geary, 2005). Over the last decades, researchers have mostly been focusing on either phonological processing as a cognitive precursor of reading and writing words (Castles & Coltheart, 2004) or on numerical magnitude understanding as the most important precursor of number processing (Siegler & Braithwaite, 2017). In this chapter, we aim at bringing together both lines of research by discussing the role of phonological and magnitude processing for the understanding of words and numbers, as well as interactions between these processes in more detail. In particular, we will address aspects of the structure and the acquisition of symbolic (both verbal and Arabic) codes in young children. Moreover, we will discuss similarities and specificities of both codes and how they acquire semantic meaning in early stages of human development. Furthermore, we will elaborate on the comorbidity between math and reading difficulties in light of the interaction between the development of symbolic codes for words and numbers. Finally, we will integrate these lines of argument

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by exemplarily reviewing the cognitive underpinnings of number transcoding (a numerical task with clear verbal aspects), focusing on the role played by different subcomponents of phonological processing.

2 Words and numbers: Common developmental footprints?

The process of mastering the representational codes for words and numbers is marked by a change from an early period when children learn the primitives and begin to construct a lexicon, to a later period in which this lexicon is fully and readily available and can be operated on. This can be observed in number transcoding tasks that demand converting numbers from different notations, such as reading Arabic digits aloud or writing Arabic numbers from dictation. Previous research investigating number transcoding performance observed relatively high frequencies of lexical errors in younger children (up to the second grade), and of syntactic errors in older children (Moura et al., 2013, 2015; Power & Dal Martello, 1990; Seron et al., 1992; Seron & Fayol, 1994). During the first years of schooling, processing of words and specifically also number words is usually more procedural and serial in nature (i.e., starting to read letter by letter and counting-based strategies to assign cardinality to sets). At this point, processing of words poses high demands on WM based on the segmentation of words into smaller units (i.e., phonemes) and their recoding (Share, 1999). Additionally, the processing of number words highly depends on the actual task at hand. For instance, in young children the precise numerical magnitude meaning of a number word is often accessed by counting-based strategies which, later on, may also be employed to solve simple calculations (Fritz et al., 2013). Additionally, both (multi-digit) number words and numbers in the form of Arabic digits are segmented in order to be processed (Bahnmüller et al., 2016; Barrouillet et al., 2004). All these processes represent a considerable challenge for children at the respective age of acquisition and depend heavily on working memory resources (Camos, 2008; Hecht, 2002; Noël, 2009).

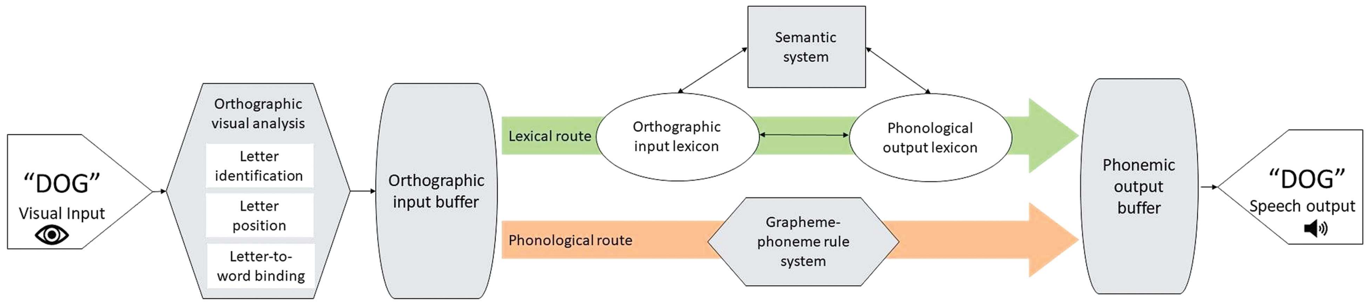
Commonalities between the acquisition of the verbal and numerical codes are reflected at the theoretical level. Brysbaert (2005) called attention to the similarities between the process of word reading, as described by the dual-route model (Coltheart et al., 2001), and the processing of single-digit numbers. In particular, Brysbaert (2005) suggested that learning of both verbal and numerical codes proceeds from initial sequential processing based on phonological and working memory resources to later more holistic/parallel and automatized forms of processing.

According to the dual-route model of single word reading (Coltheart et al., 2001, see Fig. 1a for an illustration) reading starts by the visual orthographic analysis of the written word, with identification and grouping of its graphic components in parallel, followed by serial processing of the word following different routes. Along the sublexical or phonological route, processing occurs by rules for converting written units into sound units (i.e., grapheme-phoneme conversion). Along the lexical route, familiar words, stored in a lexicon that combines contextual, visual, phonological, and orthographic information, are recognized directly, bypassing grapheme-phoneme conversions. These two routes work simultaneously and in a horse-race manner so that the more efficient route results in reading or speaking a target word out loud first. As such, reading unfamiliar words is usually associated with the phonological route, while familiar words are more likely read via the lexical route primarily. While less proficient readers might have access only to the phonological, more sequentially operating route, proficient readers can flexibly draw from both routes in parallel.

Barrouillet and colleagues (2004) also explicitly explored similarities between verbal and numerical processing in the ADAPT (A Developmental, Asemantic, and Procedural Transcoding) model of writing numbers in digital-Arabic notation – a dual-route model of number dictation (see Fig. 1b). The ADAPT model explains transcoding of verbally spoken number words to digital-Arabic numbers through the interplay of recovering content from long-term memory and applying algorithm-based conversion rules. The model suggests a first step in which verbal input is temporarily stored in a phonological buffer. In case this content matches a lexical unit stored in long-term memory, the digital form can be retrieved directly (cf. the lexical route in dual-route model of single word reading; Coltheart et al., 2001). When this is not possible, a parsing process divides the respective content into units that can be processed. At this stage, a set of procedural rules are applied sequentially processing the content held in the phonological buffer and deriving a syntactic frame which is then filled with the respective digital forms.

In general, dual-route models assume that words and number words are initially processed in a laborious sequential way at the phonemic level. As children become more experienced, lexical entries gradually develop and processing of words and some number words and digital-Arabic numbers becomes less WM demanding and increasingly based on parallel processing (Barrouillet et al., 2004). Practice in word reading allows for applying more holistic or parallel visual word processing based on recurring grapheme ensembles and their progressive

(a) Dual-route model of single word reading



(b) ADAPT model

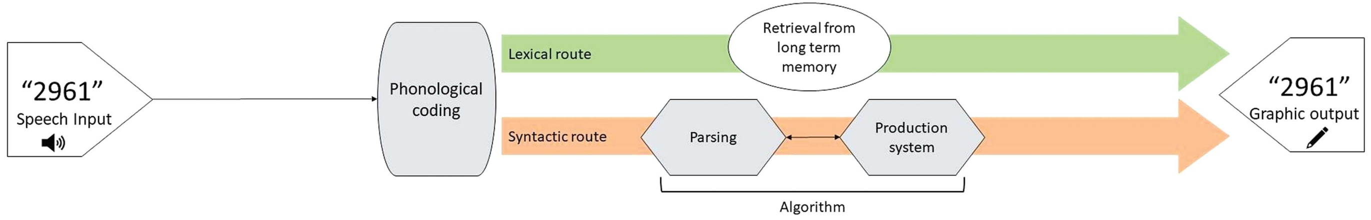


Fig. 1: Dual-Route models of (a) single word reading and (b) numbers writing in digital-Arabic notation.

association with pronunciation and meaning. Dehaene (2009) suggested that these holistic strategies are not acquired at the lexical level, eventually building a "sight lexicon," but at the sublexical level, consisting of recurring patterns of associations among graphemes digrams, such as "ll" (Treiman et al., 2018), that are processed preferentially.

Something similar to the lexicalization of word processing can occur with respect to the processing of single-digit number words and Arabic numbers. Growing experience with smaller and more frequent numbers in this range can facilitate more direct processing of these symbols, allowing fast access to the represented numerical magnitudes (Brysbaert, 2005). Empirical evidence also indicates that more frequent numerals with two or more digits with associated verbal lexical-semantic meanings may be accessed more efficiently (747, 1945, etc. See, e.g., Delazer & Girelli, 1997). However, access to and processing of the quantitative meaning of number words and Arabic numbers with two or more digits remains dependent on more laborious serial processing strategies (Bahnmueller et al., 2016).

Primary units of symbolic representations are then used to build more elaborate representations, with words leading to lexical-semantic access, and multi-digit Arabic numbers leading to the ability to represent and manipulate increasingly larger quantities in an abstract way. Figure 2 illustrates this

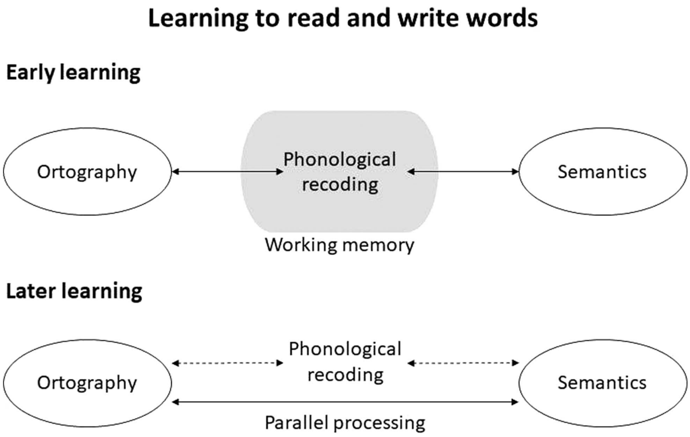


Fig. 2: In early phases of reading acquisition, associations between orthography and semantics primarily rely on sequential phonological recoding. In later phases, lexical representations are gradually built and access to semantics from orthography becomes more direct through parallel processing of sublexical subcomponents such as digrams and trigrams.

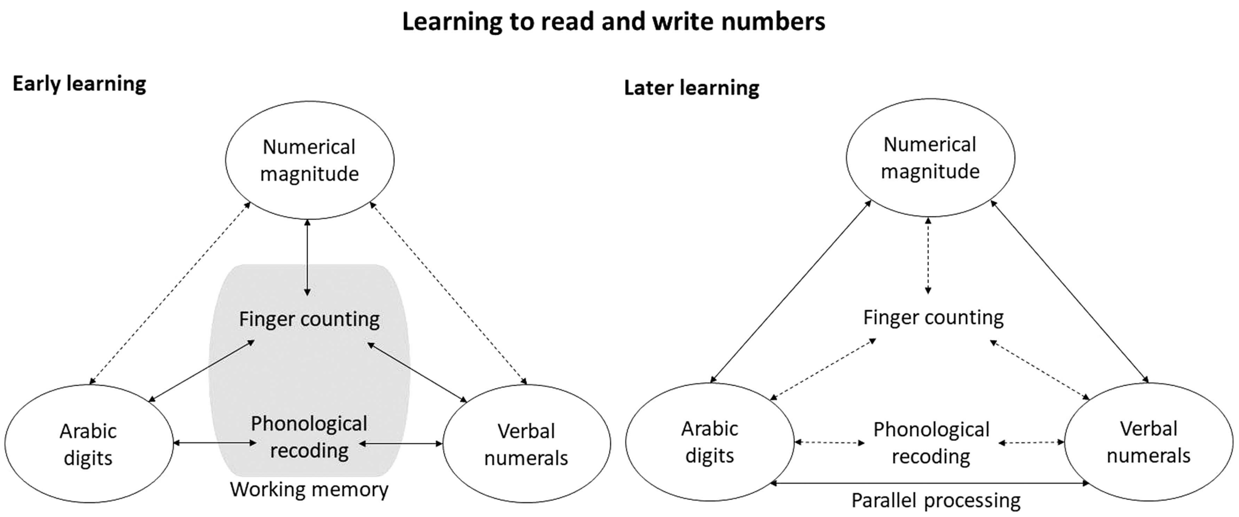


Fig. 3: In early phases, associations of numerical magnitude and their symbolic representations (i.e., Arabic digits and number words) also seem to depend on sequential processing in WM. Phonological recoding of, for instance, the counting sequence, is crucial for associating verbal and digital-Arabic representational codes. Finger counting may help offloading WM through concrete representations. With age and experience some number words and digital-Arabic numbers, at least in the single-digit range, become increasingly lexicalized. This means that in later phases of numerical processing their direct access to the corresponding quantity information depends less on sequential processing in WM. Accordingly, the importance of finger counting as a link between numerical magnitudes and number words fades out. In addition, transcoding between digital-Arabic numbers and number words also depends less on phonological recoding, at least for more frequently encountered numbers charged with verbal lexical-semantic meaning.

assumed development of associations between graphemes and lexical entries in word reading. Corresponding associations of numerical magnitude and number words and Arabic digits/multi-digit numbers are illustrated in Fig. 3.

As indicated in Fig. 2 and 3, an important difference during the acquisition of word, number word, and Arabic digit knowledge is the role of bodily experiences of fingers (for counting). Finger-based numerical representations (e.g., thumb, index, and middle finger representing three) and finger counting are extremely common (Crollen et al., 2011; Wasner et al., 2014). As finger-based representations and finger counting provide concrete representations of number magnitude, they may play an important role in offloading working memory. Thereby, resources that facilitate the acquisition of more abstract symbolic representations and calculation procedures may be set free (Alibali & DiRusso, 1999; Costa et al., 2011).

3 Shared deep structural features: Symbolic mapping and relational reasoning

The detailed mechanisms by which phonological processing mediates the development of literacy and numeracy are not yet clear. Collins and Laski (2019) proposed an analytical framework intending to foster our understanding of interactions between word and number processing during developmental progression. According to the authors, early literacy and numeracy skills differ in surface features such as the physical signs (letters, words, digits, arithmetic symbols, etc.). On the other hand, literacy and numeracy skills share some deep structural features, which rely on common processes (i.e., processing rules, principles, or schemas). These common processes may, in part, explain the observed associations between both domains. Importantly, the authors called attention to specific similarities in the deep structure of literacy and numeracy, mainly pertaining to symbolic mapping and relational reasoning.

Symbolic mapping reflects the establishing of connections between symbols and labels (i.e., identification of letters and digits as relevant codes) as well as symbols and referents (i.e., mapping of letters onto sounds and digits onto magnitudes). Relational reasoning is defined as the ability to discern meaningful patterns within otherwise unconnected information (Dumas et al., 2013). As such, relational reasoning abilities allow for making comparisons and recognizing similarities and differences between sets of information to infer meaningful relationships, structures, and patterns.

An important subcomponent of relational reasoning similarly involved in literacy and numeracy is part-whole thinking. Part-whole thinking is defined as understanding how units of information (parts) combine into larger units of meaning (wholes, cf. Fritz et al., 2013). With respect to literacy, phonemic awareness, the prime cognitive correlate of literacy, allows singling out specific phonemic segments from words to create new words (e.g., What is cup without the /c/?). As regards numeracy, part-whole thinking plays a role in recognizing that several parts can make up a whole (i.e., composing numbers of other numbers, e.g., $2+4=6$), and wholes can be divided into parts (i.e., decomposing numbers), which also underlies children's basic understanding of first arithmetic procedures (i.e., addition and subtraction, e.g., Krajewski & Schneider, 2009), but also fractions and proportions later on, e.g., Siegler et al. (2011).

Despite numbers and words sharing some features, numerical symbols are unique for many reasons. The special status of numerical symbols is attributable to the syntactic structure of number words and Arabic numbers, which imposes specific hurdles during development. In the next section the literature on the acquisition of the numerical symbols will be addressed in more detail.

4 The numerical Arabic system

Numerical representations develop side-by-side with language in children (e.g., Le Corre & Carey, 2007). Almost as early in their cognitive development as children begin to speak, they start using the first oral number words. However, it takes years of informal learning but also formal instruction until children master the use of symbolic numerical notations (Moura et al., 2013, 2015). At first, children learn to count by reciting a sequence of number words. However, these number words are still devoid of any quantitative meaning (Sarnecka & Lee, 2009). Gradually, these number words become associated with non-symbolic numerical representations (Krajewski & Schneider, 2009; Le Corre & Carey, 2007). As the mapping between the sequence of number words and their respective numerical magnitude meaning is established, children become able to successfully perform several new tasks. For instance, they may then use these number words to indicate the quantity reflected by a set (i.e., say "six" when they quickly look at a set of six objects). Additionally, they can now also produce quantities of a certain magnitude (e.g., delivering two toys requested by a caregiver). These activities are only completely developed around the age of five, when children have mastered the so-called cardinality principle, according to which the last number word recited when counting corresponds to the magnitude of the set (Le Corre & Carey, 2007). From then on, children possess a list of number words which is progressively associated with specific numerical magnitudes, which still need to be automatized and associated with other numerical codes, in particular the digital-Arabic code.

Mastering symbolic numerical codes is one of the first challenges faced by young children in math instruction at school (McLean & Rusconi, 2014). At this point in their numerical development, most children already acquired lexical entries necessary for reciting number words and recognizing single-digit Arabic numbers (Moura et al., 2013, 2015; Power & Dal Martello, 1990, 1997; Seron et al., 1992). However, they usually still struggle with larger numbers and with switching between numerical notations, this means transcoding from number words to digital-Arabic notation and vice versa. In order to successfully acquire these skills, children have to master not only the lexical and syntactic structure of number words and Arabic numbers, but also be aware of similarities and specificities of the two codes.

Learning the digital-Arabic code is, in fact, an important landmark in the development of children's numerical abilities, and one of the first important difficulties they have to deal with (McLean & Rusconi, 2014). But why is it considered and experienced as difficult? The main reason why understanding the structure of the Arabic number system is difficult may be because it is fully symbolic, and not based on any previously acquired numerical ability (e.g., counting) or acquired intuitively. In fact, the learning of the Arabic number system demands explicit and systematic instruction and it usually requires several years until children have mastered its structure (Gervasoni & Sullivan, 2007; Moura et al., 2015).

From an evolutionary perspective, representing numbers in symbolic notations was a big challenge for human civilizations. The origins of the first symbolic numerical codes go back to the time when humans developed written language and may have originated from the necessity to store and share the results of enumeration (Chrisomalis, 2004; Ifrah, 2000; Zhang & Norman, 1995). Early tally-like notations, mostly based on one-to-one correspondence, failed when larger numerical magnitudes needed to be represented (Coolidge & Overmann, 2012). Symbolic codes were then proposed, but initially they did not take advantage of a compositional place-value structure to reduce the complexity imposed by larger sequences of symbols as numerical magnitudes increased (e.g., MCMXLVIII for 1948 in the Roman code; Bender & Beller, 2018). As in other numerical notations (e.g., the Babylonian), in the Arabic number system, numbers are represented by sequences of lexical primitives (i.e., the digits 1 to 9) in accordance with a so-called place-value structure. The latter allowed for an economic representation of large numbers by only using a small set of digits. In particular, in the place-value structure of the Arabic number system, the numerical value of a digit is indicated by its position in the digit string, with the relative magnitude of a digit increasing from right to left by powers of ten. The relative magnitude of a single digit in the digit string is given by the multiplication of its absolute value and its base (following a multiplicative composition principle). The overall magnitude of a multi-digit number is given by the sum of the relative values of all digits (following an additive composition principle). For example, the overall value of 291 is equal to $2 \times 10^2 + 9 \times 10^1 + 1 \times 10^0$ (i.e., $200 + 90 + 1$). Finally, “0” (zero) is an indispensable placeholder that indicates the absence of a given power of ten in a multi-digit Arabic number.

Despite being of clear symbolic nature, the Arabic number system is also influenced by language characteristics such as, for example, the transparency of the respective number word system. Asian languages, such as Mandarin, Korean, and Japanese, are known for having highly transparent number words as they clearly reflect the place-value structure of the Arabic number system (Fuson, 1990; Miura et al., 1993). For example, numbers between 11 and 19 are spoken as “ten one” ($1 \times 10^1 + 1 \times 10^0$), “ten two” ($1 \times 10^1 + 2 \times 10^0$), and so on, until 20, which is spoken as “two tens” (2×10^1) (Fuson, 1990). Contrarily, some languages such as German and Dutch are rather in-transparent as the order of number words is inverted compared to the digital-Arabic notation. For example, the German number word for 24 is “vierundzwanzig” (literally “four and twenty”). Interestingly, previous studies indicate that children speaking languages with transparent number words seem to encounter fewer difficulties in learning number transcoding when compared to speakers of languages with less transparent number words such as English (e.g., thirteen instead of ten three; Miura et al., 1993) and German (e.g., Moeller et al., 2015). For instance, one consistent finding is that a large portion of transcoding errors observed in children speaking languages with in-transparent number words like German, Dutch, or Czech are related to the inversion property of the verbal number system (e.g., Zuber et al., 2009; Moeller et al., 2015; Pixner et al., 2011a; Pixner et al., 2011b).

The complexity of the Arabic number system for young students becomes evident when we consider how performance in number transcoding (i.e., Arabic number writing and reading) increases with age. When investigating Italian speakers, Power and Dal Martello (1990) observed that typically developing first graders were well able to write two-digit numbers flawlessly but experienced problems when writing down three- and four-digit numbers. Interestingly, these difficulties were more pronounced for Arabic numbers with internal zeros (e.g., 1007). This is well in line with more recent findings by Camos (2008). When investigating the performance of French second graders, Camos (2008) also found that these children were perfect in writing Arabic numbers up to 100 and committed fewer errors in three-digit, as compared to four-digit, Arabic numbers. Using a longitudinal design, Seron, Deloche and Nöel (1992; see also Seron & Fayol, 1994) assessed number transcoding skills of second and third graders three times within one school year and reported performance improvements over time with overall better performance for the Arabic number reading as compared to the Arabic number writing condition. In particular, second graders showed an improvement in performance from the beginning to the end of the school year. On the other hand, third graders showed only a small improvement due to ceiling effects from the middle of the school year on. Finally, Moura et al. (2015) studied writing of one- to four-digit Arabic numbers in Brazilian children from first to fourth grades and observed significant improvements from first to third grades, but not from third to fourth grades, substantiating the idea of a plateau or ceiling effect from the third grade onward.

Mastery of the place-value structure of the Arabic number system by children has received increasing research interest recently. This is mostly due to its importance for succeeding in school but also everyday life in general (e.g., Gervasconi & Sullivan, 2007). In the educational context, mastery of the place-value structure of the Arabic number system allows children to represent larger (multi-digit) numbers, and to apply more sophisticated calculation strategies. Not surprisingly, early mastery of the place-value structure of the Arabic number system was found to be predictive of later mathematics achievement. Moeller et al. (2011) administered several numerical tasks to first graders and observed that place-value understanding, assessed by multi-digit Arabic number transcoding and two-digit number magnitude comparison, was highly predictive of performance in multi-digit addition but also math grades two years later. More recently, Lambert and Moeller (2019) showed that difficulties in two-digit addition (in particular in problems requiring a carry over, e.g., 15 + 17 = __) in children with mathematics learning difficulties (MLD) were driven by deficits in their place-value understanding.

Moreover, employing an Arabic number writing task, Moura et al. (2013) showed that children with MLD experienced pronounced difficulties when required to write more complex Arabic numbers (i.e., three- and four-digit Arabic numbers, and Arabic numbers with internal zeros, e.g., 405). Importantly, the most frequently observed errors were due to insufficient syntactical understanding of the place-value structure of the Arabic number system (e.g., writing three hundred forty-five as 300405). Interestingly, these errors were even more common in children with MLD.

Besides requiring specific understanding of the place-value structure of the Arabic number system, processing multi-digit Arabic numbers is also demanding with respect to WM resources. Camos (2008) studied number transcoding in 7-year-old children and found a strong positive association between transcoding performance and WM capacities. More specifically, a critical role for visuo-spatial and central executive components of WM in number transcoding was reported by Zuber et al. (2009) when investigating syntactic errors (such as unit-decade inversion) produced by typically developing German-speaking children in number transcoding.

Importantly, the significant role of WM for number transcoding may reflect one of the underlying factors associated with specific learning difficulties in the domains of both mathematics (Salvador et al., 2019) and reading (Peterson & Pennington, 2015). These respective developmental disabilities frequently co-occur and, in the next sections, we discuss hypotheses put forward to explain this high comorbidity. Moreover, we specifically focus on hypotheses relating phonological WM, as well as other subcomponents of phonological processing (namely phonemic awareness and lexical access) to developmental disabilities in both domains. Afterward, we discuss studies that investigated the role of phonological processing in number transcoding, suggesting that, besides WM, phonemic awareness and lexical access should also be taken into account when it comes to the evaluation of subjacent factors to Arabic number processing.

5 The association between math and reading disabilities

In a meta-analysis, Joyner and Wagner (2019) found that students suffering from MLD are over two times more likely to also present a reading disability compared to children that do not have MLD. According to Moll et al. (2019), basic linguistic skills such as phonemic awareness may be precursors not only for later reading skills but also for verbal numerical skills, such as counting and transcoding, which in turn were found to underlie later arithmetic skills (see above).

The high comorbidity rate for math and reading difficulties may be explained by the double deficit hypothesis (Landerl et al., 2004), according to which children who present both learning difficulties suffer from simultaneous deficits in phonological processing and the processing of number magnitude. In contrast, Simmons and Singleton (2008) suggested a common deficit account to describe cognitive impairments associated with difficulties in both reading and mathematics. According to these authors, MLD may be caused by the phonological deficits commonly associated with dyslexia. It is assumed that phonological representations of dyslexic children are weak, which leads to an impairment in cognitive processes that demand and build on phonological codes. In particular, Simmons and Singleton (2008) proposed the weak phonological representation hypothesis, according to which the poorly specified nature of phonological representations would lead to poor performance in tasks that involve the retention, retrieval, or manipulation of phonological codes. Because Arabic number writing requires access to the verbal representation of number words, it seems sensible to assume that children's phonological processing abilities should also influence their numerical (i.e., transcoding) attainment.

With respect to the high comorbidity rate between math and reading difficulties, Moll et al. (2014) proposed that mathematics has both verbal and nonverbal components and poor performance may be due to different patterns of deficits in verbal and/or nonverbal number processing. The authors assessed children from 6 to 12 years and concluded that children with both reading and math difficulties presented an additive profile of deficits. In line with this argument, Jordan (2007) suggested that reading deficits aggravate – but not necessarily cause – math difficulties, because children with both difficulties would also struggle in using language-based compensatory mechanisms.

For instance, when children have to write Arabic numbers to dictation, the respective input is verbal. Hence, children must be able to differentiate between speech sounds to correctly comprehend the verbal number word that should be transcoded into the digital-Arabic notation. De Clercq-Quaegebeur et al., (2018) assessed arithmetic and number processing abilities of 47 dyslexic French children and found their performance to be lower than one standard deviation below the mean on number transcoding tasks. This result supports the claim that, independently of math learning difficulties, impairments in phonological processing may impact number transcoding performance.

However, most studies on children with reading difficulties, who present phonological processing deficits, have focused on their general arithmetic performance, and did not explore their performance in basic number processing in a differential way (e.g., De Smedt, 2018; Simmons & Singleton, 2008). As such, it is still not clear whether number transcoding may be consistently impaired in these children because of its verbal processing components when transcoding from verbal number words to digital-Arabic notation. Despite this potential impact of phonological processing on basic number processing skills, to the best of our knowledge, there are no studies so far that systematically investigated the association between phonological processing and number transcoding in more depth.

6 Words and numbers: The role of phonological skills and WM

As outlined in the first section, both the dual-route model of single-word reading and the ADAPT model of Arabic number writing assume an important role of phonological processes for the acquisition of the respective symbolic codes. The term "phonological processing" was proposed to refer to a set of cognitive abilities associated with literacy acquisition such as (i) the speed of phonological recoding in lexical access (referring to the recoding of a written stimulus into a sound-based representation to get from the written word to its lexical referent) (e.g., assessed by rapid automatized naming tasks), (ii) processes associated with maintaining sound-based representation in working memory (e.g., measured using verbal span tasks), and (iii) phonemic awareness, reflecting awareness of the sound structure of language (e.g., assessed by phoneme deletion tasks; Wagner & Torgesen, 1987). This set of abilities seems also relevant to number processing.

Lopes-Silva et al. (2014) assessed children's general cognitive abilities, verbal and visuo-spatial WM, non-symbolic magnitude comparison, phonemic awareness, and verbal to Arabic number transcoding in a sample of 172 children from second to fourth grades. At first glance, a hierarchical regression model showed that verbal WM was a significant predictor of transcoding after considering effects of age and general cognitive abilities. However, adding phonemic awareness in a third step of the regression analyses led to the exclusion of verbal WM. Therefore, the authors conducted path analyses including all of the previous measures to determine possible mediation effects on number transcoding. When phonemic awareness was not included as a mediator of the influence of verbal WM on number transcoding, model fit indices were not acceptable. The model in which the effect of WM was partially mediated by phonemic awareness was the one fitting the empirical data best indicating that this phonological skill is associated specifically with number transcoding. Both phonemic awareness and phonological working memory can thus be interpreted as indexes of the quality of children's phonological representation which may influence performance on numerical tasks requiring number words representations, such as number transcoding.

Phonemic awareness has also been consistently associated with reading performance (Peterson & Pennington, 2015; Vellutino et al., 2004). To extend this result, possible shared associations between phonemic awareness and digital-Arabic as well as word writing and reading skills were investigated. Lopes-Silva et al. (2016) aimed at disentangling the role of phonemic awareness and its impact on verbal to Arabic transcoding tasks as well as on single-word reading and spelling, controlling for other cognitive variables such as WM. The authors conducted a series of hierarchical regression models with scores of reading and writing of single words and Arabic numbers as dependent variables. They observed that performance on each numerical task (i.e., reading or writing Arabic numbers) was predicted by the corresponding verbal tasks (i.e., reading or spelling words) and vice versa as well as by phonemic awareness – even beyond the influence of general cognitive abilities. Phonological WM was also significantly associated with word reading, but to a smaller extent as compared to the influence of phonemic awareness. Interestingly, phonological WM was not associated with number transcoding. Potentially, this was due to possible shared variance with phonemic awareness. In addition, Teixeira and Moura (2020) observed that children with reading difficulties also present difficulties in writing Arabic numbers, committing both syntactic and lexical errors, whereas lexical errors were hardly observed in typically developing children. These difficulties may be explained by differences in phonological processing abilities, mainly with respect to phonemic awareness, but also regarding speed of lexical access and phonological memory.

Adding to the studies mentioned above, Batista et al. (in preparation) investigated the association between phonological processes, WM and Arabic number transcoding more thoroughly by considering different aspects of phonological processing as well as different WM aspects in the same study. In particular, in a sample of third and fourth graders they assessed variables including phonemic awareness, speed of lexical access as well as verbal and visuo-spatial WM. Hierarchical regressions controlling for influences of general cognitive abilities showed that Arabic number writing performance was predicted by visuo-spatial WM and lexical access. Interestingly, considering lexical access in the regression models led to the exclusion of phonemic awareness.

These findings are in line with the weak phonological representation hypothesis by Simmons and Singleton (2008), according to which phonological processing deficits impair aspects of numerical processing that require the manipulation of verbal codes (transcoding but also counting, arithmetic fact retrieval, etc.), while other nonverbal aspects of number processing that rely less on verbal codes (e.g., magnitude manipulations, estimation, subitizing) should remain unimpaired. In number transcoding, the input is verbal; hence, the child must be able to differentiate between speech sounds to correctly comprehend the verbal number word that needs to be transcoded into Arabic notation. The results reviewed above suggest that the poor phonological representation hypothesis may also hold for numerical transcoding tasks in the sense that number transcoding should also be interpreted as a verbally mediated numerical ability, at least partially relying on phonological processing.

However, the actual working mechanisms underlying the association between phonological processing and numerical abilities more broadly remains unclear so far, even though above-described results may allow for a preliminary conclusion with respect to the interplay of phonological processing and number transcoding abilities. To further substantiate our suggestions, future studies should simultaneously consider different subcomponents of phonological processing (i.e., lexical access and phonemic awareness) to investigate their specific influences. To illustrate this, lexical access has so far been associated with arithmetic fact retrieval (De Smedt, 2018) and fluency in reading words (Papadopoulos et al., 2016). In a similar vein, Geary (1993) suggested that the comorbidity between math and reading difficulties may be associated with deficits in lexical access. Moreover, a meta-analysis by Koponen et al. (2017) investigated the association of lexical access with a range of numerical abilities. Results indicated that rapid automatized naming was more strongly associated with simple numerical tasks (e.g., arithmetic fluency) than with more complex ones (e.g., multi-digit calculations). Also, lexical access is required when processing numerical or operational symbols in simple tasks, while in more complex calculations, multiple cognitive skills are involved (e.g., Koponen et al., 2017). Regarding number transcoding, deficits in lexical access may lead children to commit more lexical errors due to incorrect access to the digital-Arabic representation corresponding to the dictated verbal number word (Barrouillet, 2004).

However, phonemic awareness may be strongly associated with lexical access to numerical symbols. In many languages investigated so far, there are phonologically similar number words that one may confuse – especially children – and specific strategies may be required to differentiate them orally. For instance, in German “zwei” (two) and “drei” (three) sound quite similar. When dictating a phone number people could say “zwo” instead of “zwei,” to avoid errors. This is also observed in Portuguese for “três” (three) and “seis” (six), on which people often say “meia” (half a dozen) instead of “seis” (six) to avoid misunderstandings. Furthermore, it is obvious that an accurate understanding of the phonological structure of verbal number words is crucial to derive the corresponding Arabic symbols correctly. Thus, it is especially important to investigate the role of lexical access *and* phonemic awareness as subcomponents of phonological processing because most studies only considered influences of phonological WM so far (see Camos, 2008; Moura et al., 2013; Zuber et al., 2009) – even though the ADAPT model suggests that the first step of transcoding from verbal number words to digital-Arabic notation is the phonological encoding of the respective number word.

Taken together, we reviewed evidence suggesting that phonological processes are important not only for acquiring word reading and writing but also for reading and writing (multi-digit) numbers. However, it is not clear from previous research which role different components of phonological processing may play – in particular in reading and writing (multi-digit) numbers. From a developmental point of view, it seems that phonological processing might be important in early stages of the acquisition of basic numerical and arithmetic abilities whereas the exact role of phonological processes in numerical cognition in adults is controversial (De Rammelaere et al., 2001; De Rammelaere & Vandierendonck, 2001; DeStefano & LeFevre, 2004; Seitz & Schumann-Hengsteler, 2000). In this context, initial evidence also indicates that the relevance of phonological and visuospatial working memory may vary considerably with age and experience (Krajewski & Schneider, 2009; McKenzie et al., 2003). This may suggest that there might be different paths to acquire symbolic numerical and arithmetic abilities in the transition from kindergarten to primary school, one verbal (phonological) and the other visuospatial (LeFevre et al., 2010).

7 Conclusions

Reading and writing words as well as numbers are core challenges elementary students face in their first years of schooling. Despite considerable bodies of research dedicated to each of these tasks, there is still a lack of research on potential overlaps between the cognitive mechanisms underlying word and symbolic number processing, and how they interact during children's cognitive development. Recent results indicated a prominent role for phonological skills for the development of both reading and numerical abilities. Moreover, evaluating performance in tasks that simultaneously draw on phonological as well as numerical aspects, such as number transcoding, seems to be particularly informative. Laborious and sequential phonological processing may be crucial for the initial processing of both words and symbolic numbers in children's development. Practice allows for more efficient forms of processing of words and smaller and more frequent Arabic digits. These may then form the building blocks for reading comprehension and processing of more complex multi-digit symbolic numbers. Better understanding of how representations of words and numbers are associated may foster our understanding of the cognitive underpinnings of learning to read and write words and numbers and, as a consequence, the diagnosis of specific learning difficulties.

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