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Separate mechanisms for number reading and word reading: Evidence from selective impairments°

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Do number reading and word reading use the same cognitive mechanisms? We examined this question through the looking glass of dissociations between impairments in number and word reading.

We report two women with selective deficits in number reading, who read words normally. An examination of their impairment pattern indicated that the specific locus of their number reading deficits is in processes that handle the number's structure: both were impaired in parsing a digit string into triplets, and one of them was also impaired in generating the number's verbal structure. In contrast to their structural deficits in number reading, their word reading was completely intact, including the structural processes in word reading (morphological analysis and assembly).

We present this dissociation in the framework of a broader effort to examine dissociations between specific components in number and for word reading. We went beyond general word-number dissociations: we used detailed cognitive models for word reading and number reading, and analyzed them in order to identify which components of the number reading process are homologous to which components of words reading. We then show that even these homologous processes are dissociable: an examination of previously-reported dissociations, completed by the case studies presented here, indicated that each of the specific homologous sub-processes of word/number reading can be selectively impaired. We conclude that although the word and number reading pathways show much similarity, they are almost entirely separate.

1. Introduction

Is word reading implemented by a set of highly specialized mechanisms, dedicated to the processing of orthographic material, or is it accomplished by domain-general mechanisms, which serve not only the processing of words but also other functions? The present study examined this issue by looking into the relation between word reading and number reading – a comparison that can help identifying the range of stimuli processed by the reading mechanisms. This could improve our understanding of reading, of its developmental and evolutionary origins, and may shed light on the role of domain-specific versus domain-general mechanisms in implementing complex cognitive functions (Dehaene, Piazza, Pinel, & Cohen, 2003; Hauser, Chomsky, & Fitch, 2002; van de Cavey & Hartsuiker, 2016; Whorf, 1940; Wilson et al., 2015).

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From a clinical perspective, understanding the relation between word reading and number reading could be crucial for a more accurate assessment and treatment of disorders of word reading (dyslexia) and disorders of number reading (which we propose to term “dysnumeria”).

We start with a theoretical review of the relations between the reading aloud of words and of numbers. This review is done in two levels of granularity: first, we compare the two types of reading in a relatively global manner, describing word-number reading dissociations without addressing the exact impairment within these processes (Section 1.1). Then we drill down into higher granularity level: we use detailed cognitive models for word reading and number reading, and analyze them to identify which components of the number reading process are homologous to which components of words reading (Section 1.2). We then review previously-reported dissociations and examine whether these homologous processes are dissociable.

In the experimental part of this study (Sections 2-4), we focus on homologous processes related with structural (syntactic) processing, for which a dissociation has not yet been reported. We present two women who had specific deficits in structural processes in number reading, whose word reading – including the homologous structural processes – was intact.

1.1. Word reading versus number reading

Words and numbers have much in common: both are written as character strings and must comply with certain structural rules, and both types of strings – letters and digits – can be converted to a verbal-phonological format. Nevertheless, words and numbers are also quite different: the language of numbers is merely a small subset of natural language, and its syntax is simpler. Letter and digit strings are also different in their meaning: both words and numbers may refer to semantic concepts (“orange”, “Peugeot 205”), but numbers also have meaning as quantities. The different semantics of words and numbers may have a major effect on the reading mechanisms, and may have shaped the specialization of word reading and number reading to different brain circuits. One idea is that the word reading mechanisms have evolved to utilize brain circuits with high neural connectivity to the brain regions that process language, whereas number reading mechanisms have evolved to utilize brain circuits with high neural connectivity to the brain regions representing quantities (Hannagan, Amedi, Cohen, Dehaene-Lambertz, & Dehaene, 2015).

An important method for investigating the relation between word reading and number reading is the examination of individuals with reading difficulties. An impairment in a process that serves only words or only numbers should affect only the reading of the relevant stimulus type, but an impairment in a shared process would affect both stimulus types. Dissociations between deficits in word reading and number reading can indicate that word reading and number reading are implemented by separate cognitive processes.

In many cases, cognitive impairments affect the reading of words as well as the reading of numbers (Cohen, Dehaene, & Verstichel, 1994; Denes & Signorini, 2001; Katz & Sevush, 1989; Shen et al., 2012; Starrfelt, Habekost, & Gerlach, 2010). This could suggest that word reading and number reading are implemented, at least in part, by shared cognitive mechanisms (Denes & Signorini, 2001). However, in other cases, dissociations were observed between word reading and number reading, suggesting distinct reading mechanisms for words and numbers. Disorders of word reading sometimes spare number reading (Anderson, Damasio, &

Damasio, 1990; Cohen & Dehaene, 1995; Friedmann, Dotan, & Rahamin, 2010; Friedmann & Nachman-Katz, 2004; Greenblatt, 1973; Hécaen & Kremin, 1976; Leff et al., 2001; Lühdorf & Paulson, 1977; Nachman-Katz & Friedmann, 2007; Sakurai, Yagishita, Goto, Ohtsu, & Mannen, 2006; Starrfelt, 2007; Temple, 2006), and disorders of written word comprehension sometimes spare the comprehension of written digit strings (Cohen & Dehaene, 2000; Dalmás & Dansilio, 2000; Ingles & Eskes, 2008; Miozzo & Caramazza, 1998; but some such dissociations were criticized as statistically unconvincing, Starrfelt & Behrmann, 2011). The opposite dissociation was also reported: disorders of number reading sometimes spare word reading (Basso & Beschin, 2000; Cipolotti, 1995; Cipolotti, Warrington, & Butterworth, 1995; Marangolo, Nasti, & Zorzi, 2004; Priftis, Albanese, Meneghello, & Pitteri, 2013; Temple, 1989). Word reading and number reading also give rise to different brain activation patterns (Carreiras, Monahan, Lizarazu, Duñabeitia, & Molinaro, 2015; Carreiras, Quiñones, Hernández-Cabrera, & Duñabeitia, 2015; Hannagan et al., 2015; Roux, Lubrano, Lauwers-Cances, Giussani, & Démonet, 2008; Shum et al., 2013).

1.2. A detailed comparison between the sub-processes of word reading and number reading

Comparing word reading and number reading holistically as we did above, treating each of the two reading mechanisms as a whole, is merely a first step. The next step should acknowledge that reading involves several different sub-processes, and it is possible that some of them are dedicated to words or to numbers whereas others are shared. This is the approach we take in the present study: we examine the question of dedicated versus shared processing separately for each of the sub-processes involved in reading. To this end, we review the cognitive mechanisms involved in word reading and number reading (Sections 1.2.1 and 1.2.2, respectively), we identify potential homology between specific sub-processes of word reading and number reading (Section 1.2.3), and we review dissociations between such homologous processes (Section 1.2.4).

1.2.1. The cognitive architecture of word reading

The dual-route model of word reading (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Coslett, 1991; Ellis & Young, 1988; Forster & Chambers, 1973; Friedmann & Coltheart, 2018; Marshall & Newcombe, 1973; Patterson & Morton, 1985) describes several different processes involved in reading single words (Fig. 1). Reading starts with visual analysis of the letter string: encoding the letter identities, their relative positions within a word, and their association to words (Coltheart, 1981; Ellis, 1993; Ellis & Young, 1996; Ellis, Flude, & Young, 1987; Friedmann & Gvion, 2001; Friedmann & Haddad-Hanna, 2012, 2014; Friedmann, Biran, & Gvion, 2012; Humphreys, Evett, & Quinlan, 1990; Kezilas, Kohnen, McKague, & Castles, 2014; Marshall & Newcombe, 1973). The orthographic-visual analyzer, probably using a graphemic input buffer at this processing stage, also performs an initial morphological decomposition of the word (Beyersmann, Castles, & Coltheart, 2011; Friedmann, Gvion, & Nisim, 2015; Friedmann, Kerbel, & Shvimer, 2010; Longtin & Meunier, 2005; McCormick, Rastle, & Davis, 2008, 2009; Rastle, Davis, & New, 2004; Reznick & Friedmann, 2015; Taft & Forster, 1975). The reading process then continues in two pathways: in the lexical pathway, the word is first found in a lexicon that contains the orthographic forms of all familiar words (Coltheart & Funnell, 1987; Friedmann & Lukov, 2008). The lexical entry is used to retrieve the word's phonological components (phonemes, metric structure) from a phonological output lexicon (Butterworth, 1992; Levelt, 1992; Nickels, 1997; Nickels & Howard, 1994). The second pathway of word reading, the sub-lexical pathway, does not rely on lexicons: the sequence of letters is translated into a phonological sequence by the grapheme-to-phoneme converter, which relies on language-specific conversion rules (Coltheart, 1978; Schmalz, Marinus, Coltheart, & Castles, 2015). In both the lexical and the sub-lexical pathways, the phonological components of the word are finally merged in the phonological output buffer (Butterworth, 1992; Dell, 1988; Dotan & Friedmann, 2015; Friedmann, Biran, & Dotan, 2013; Laganaro & Zimmermann, 2010; Levelt, 1992; Levelt, Roelofs, & Meyer, 1999; Nickels, 1997), and the word is sent to the articulation stages.

A branch of the lexical route handles word comprehension: a word that was identified in the orthographic input lexicon activates the information in the semantic-conceptual system, a process that allows the reader to get the word's meaning. The semantic system is also connected to the phonological output lexicon and the rest of the production pathway. This latter connection is the path of word retrieval during speech production (Friedmann et al., 2013).

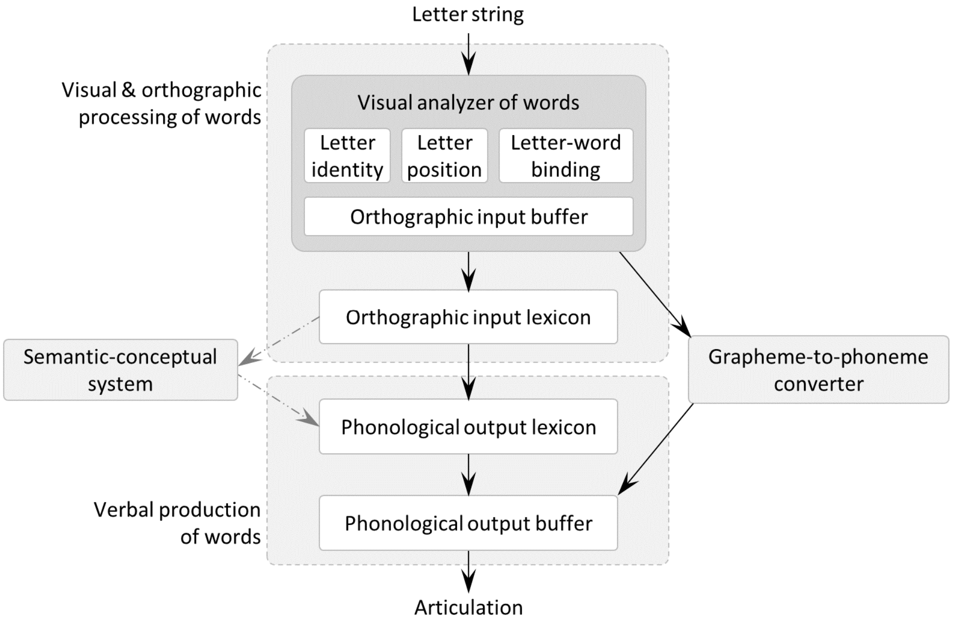

Fig. 1. A cognitive model of word reading (Friedmann & Coltheart, 2018). The orthographic-visual analyzer extracts the letter identity and order from the letter string, and binds letters to words. In the lexical pathway (middle column), the letters are used to identify the written word in the orthographic input lexicon. The phonological output lexicon, which contains a corresponding lexical entry, provides the phonological form of the word. These components are merged in the phonological output buffer and then articulated. In the sub-lexical pathway (right), letter strings are read by directly converting graphemes (letters or letter groups) to phonemes. Access to the semantic system (left) allows comprehension of the word, and access from the semantic system to the phonological output lexicon as allows the production of words.

1.2.2. The cognitive architecture of number reading

Reading numbers aloud involves parsing a digit string and translating it into a sequence of number words. The visual analysis of digit strings and the verbal production of number words are implemented by separate cognitive mechanisms, as indicated by several neuropsychological case studies (Bencini et al., 2011; Benson & Denckla, 1969; Cohen & Dehaene, 1995; Cohen, Verstichel, & Dehaene, 1997; Delazer & Bartha, 2001; Dotan & Friedmann, 2015; Dotan, Friedmann, & Dehaene, 2014; Marangolo et al., 2004; Marangolo, Piras, & Fias, 2005; McCloskey, Sokol, & Goodman, 1986; Noël & Seron, 1993) and brain imaging studies (Dehaene & Cohen, 1995; Dehaene et al., 2003).

Turning to finer-grained details, we describe a cognitive model that we developed (Dotan & Friedmann, 2018), which merges and extends previous models (Cohen & Dehaene, 1991; McCloskey, 1992; McCloskey et al., 1986). The model (Fig. 2) postulates that within the visual analysis of digits, the identities and order of digits are encoded by two separate processes (Cohen & Dehaene, 1991; Friedmann, Dotan, & Rahamim, 2010). Another set of numeric-visual analysis sub-processes extracts the number's decimal structure – the number of digits, the positions of 0, and the grouping of digits into triplets. This decimal structure is used by the verbal production processes to generate a *number word frame*.

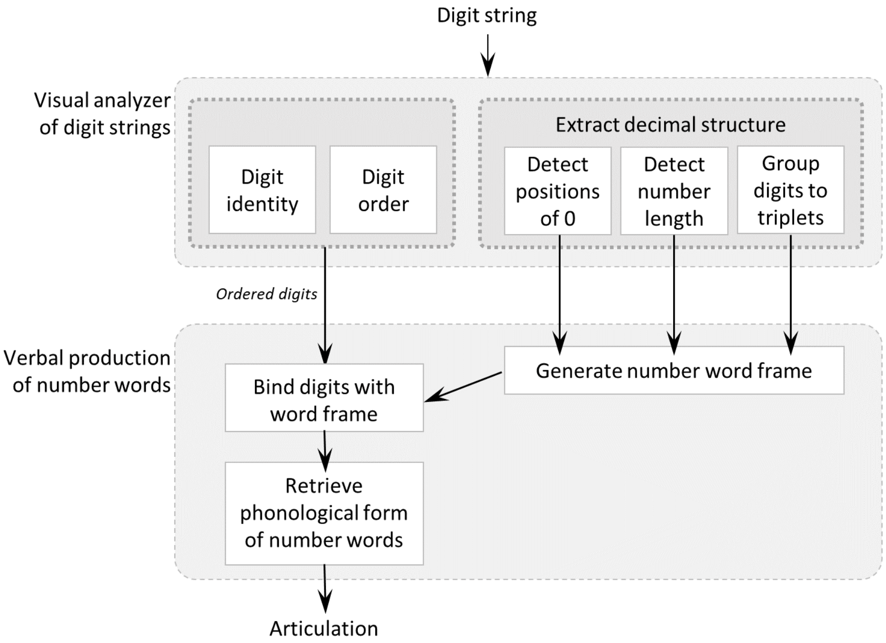

Fig. 2. A cognitive model for number reading. The digit string is parsed by 5 sub-processes within the numeric-visual analyzer. These processes detect the digit identity, the digit order, and several aspects of the number's decimal structure: its length, the positions of 0, and its triplet structure. The decimal structural information is used to obtain a number word frame – an almost-full specification of the sequence of number words to produce, which lacks only the specific digit values. The word frame is bound with the corresponding ordered digit identities, resulting in a full specification of the words to produce. The phonological form of each word is then retrieved and sent to articulation.

Conceptually, the number word frame is a representation of the number's verbal structure. Concretely, it is a sequence of word specifiers, each of which can be the lexical class of a number word (e.g., ones, tens, teens), a decimal word (“thousand”, “hundred”), or a function word (“and”). Thus, the word frame specifies the verbal number fully except the specific digit values. For example, the word frame for 5012 is *{_:ones} [thousand] [and] {_:teens}*. The word frame is bound with the ordered digit identities (provided by the visual analyzer’s digit identity encoder and digit order encoder), resulting in an exact specification of the words to produce – *[5:ones] [thousand] [and] [2:teens]*. This specification is used to retrieve the words from dedicated phonological stores (Dotan & Friedmann, 2015, 2018; McCloskey et al., 1986).

This number reading model is supported by several studies that reported highly specific error patterns in number reading (Benavides-Varela et al., 2016; Cipolotti, 1995; Cohen & Dehaene, 1991; Cohen et al., 1997; Dotan & Friedmann, 2015, 2018; Dotan et al., 2014; Friedmann, Dotan, et al., 2010; McCloskey et al., 1986; Noël & Seron, 1993). The model aims to be applied to any language, including Hebrew, in which the present study was conducted[1]. In Hebrew, words are written from right to left, but digit strings are written from left to right, like in English, using Arabic digits (0, 1, 2, 3, 4, 5, 6, 7, 8, 9). A comma separator can be optionally added every 3rd digit (from the right, e.g., 23,456,789). The syntax of the Hebrew system of number words is very similar to that of English, with number words for ones, teens, and tens, and with special words for the multipliers “hundred” and “thousand”[2].

The model describes how we read aloud visually-presented digit strings. Another question is how we understand them. Numbers have two different kinds of meanings, corresponding with two different comprehension mechanisms. Some digit strings are familiar lexical entries that, like words, denote semantic concepts – e.g., “Peugeot 306” and George Orwell’s “1984”; and any digit string represents a quantity via a mechanism known as the Approximate Number System (Dehaene, 1992; Dehaene & Cohen, 1995; Dehaene et al., 2003; Feigenson, Dehaene, & Spelke, 2004; Mou & VanMarle, 2014; Nieder, 2013; Piazza, 2010). A digit string can be converted to quantity by a set of dedicated cognitive processes (Dotan & Dehaene, 2016, 2017; Nuerk & Willmes, 2005). The digits-to-quantity conversion pathway presumably involves the numeric-visual analyzer (presented in Section 1.2.2), but it does not involve the verbal production mechanisms (Dotan et al., 2014).

1.2.3. Possible parallels between word reading and number reading mechanisms

Having described the models for word reading and number reading, we can now rely on these models to examine the questions of shared and separate mechanisms between the two processes. Starting with similarities between the two models, perhaps the clearest similarity is that both words and numbers involve visual / orthographic input processes (words: orthographic visual analyzer, orthographic input lexicon; numbers: numeric visual analyzer)

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[1] Different languages use different scripts for digits (e.g., ٠١٢٣٤٥٦٧٨٩ in Arabic) and different lexicons of number words. Languages differ also in the structure of verbal numbers. For example, the order of number words agrees with the order of digits in most languages, but in some languages, the units word precedes the decades word (e.g., in German and Arabic). Another example is the irregularity of French numbers 71-79 and 91-99, whose verbal form is [decades] and [teens], and whose decade word differs from the decade digit by 1 (e.g., 74 = soixante-et-quatorze, “sixty and fourteen”). To accommodate these differences, the model assumes that some of the sub-processes within verbal production are language-dependent, whereas other sub-processes are language-general (Dotan & Friedmann, 2018).

[2] Hebrew differs from English in lexical aspects of the phonological realization of the numbers. For example, in Hebrew there are lexical items corresponding to two-hundred and two-thousand; and teens, tens, hundreds, and thousands are produced using the construct state nominal morphology.

and verbal / phonological production processes (words: phonological output lexicon, phonological output buffer; numbers: phonological retrieval, generation of number word frames).

Parallels can be found also for higher-granularity processes. For words and numbers alike, visual analysis of the character string involves distinct processes to encode the identity of characters and their relative order. Another parallel concerns the distinction between lexical and structural processes. Models of symbolic number processing typically categorize processes as “lexical”, handling the identities of single elements (digits and number words), or as “syntactic”, handling the relations between these elements, i.e., the number’s decimal or verbal structure[3]. This distinction between single-element processing and structure processing may apply to word reading too: some processes handle single letters or phonemes, whereas other processes handle the word’s morphological structure. We propose that the so-called syntactic processes in number reading are homologous to morphological processes in word reading. This idea is supported by studies showing that structural information (in numbers) and morphological information (in words) show important parallels: structural/morphological information is extracted by the orthographic-visual analyzer of words (Friedmann & Coltheart, 2017; Friedmann et al., 2015; Rastle & Davis, 2008; Rastle et al., 2004; Reznick & Friedmann, 2009, 2015; Taft, 2004) and by the numeric-visual analyzer of numbers (Dotan & Friedmann, 2018); and in verbal production, there seem to be similar pathways for handling number words and morphemes (this is explained in further detail below, in Section 1.2.4.3).

In spite of these similarities between word and number reading, they are not completely parallel. Two issues stand out as major differences between reading aloud of words and numbers. First, a letter string is converted to one word, whereas a digit string is converted to multiple words; in a sense, the verbal form of a multi-digit number resembles a whole phrase more than a single word. Second, any digit string yields a valid number (except leading zeros), but letter strings are subject to lexical, orthographic, phonological, and morphological restrictions. Most digit strings are not lexically familiar and are not processed as whole lexical units, but familiar words enter the orthographic and phonological lexicons. In this respect, number reading may parallel the sub-lexical route of word reading (Denes & Signorini, 2001). On top of these two differences, even when word and number reading involve potentially parallel processes, these processes seem to be different when examined in detail. For example, both word reading and number reading involve orthographic/numeric visual analyzers that extract structural/morphological information about the letter string or digit string, but the nature of this information is different in the two cases: morphemes for words, decimal structure for numbers.

1.2.4. Dissociations and associations between specific processes of word and number reading

We now turn to review studies that compared word reading and number reading (also see a review in Starrfelt & Behrmann, 2011). Per our approach in the present study, we restrict this review to studies that compared specific sub-processes of reading.

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[3] Note that the term “lexical” is used with different meanings in the literatures of word and number processing: for numbers, “lexical” refers to processing the identity of a single digit or number word; for words, “lexical” denotes familiar words, for which we store some information in a lexicon.

1.2.4.1. Associations pertaining to peripheral processes

Word-number associations were found only in peripheral processing stages. With respect to the visual processing mechanisms, some researchers argue for shared mechanisms for processing letters and digits. These shared mechanisms include early visual processes such as processing the visual image, encoding visual features, etc., and may also include the identification of single characters and their classification as letters or digits (McCloskey & Schubert, 2014; Schubert, 2017). Other researchers posit that the early stages in the identification process are shared, but the processing of letters and digits diverges at some point (Grainger & Hannagan, 2014; see Schubert, 2017, for a review of models of character identification mechanisms, and a discussion of the possible sources for differences between letter and digit identification).

Articulation mechanisms, which handle oral production of the already-retrieved phonological forms, may serve words and numbers alike. In support of this view, word-number dissociations were observed for pre-articulation deficits, but an articulation disorder (apraxia) seems to have similar effects on number words and non-number words (Dotan et al., 2014; Shalev, Ophir, Gvion, Gil, & Friedmann, 2014).

1.2.4.2. Visual analysis of letters and digits

Current research clearly shows a stage of orthographic-visual analysis for words, and numeric-visual analysis for numbers. Is there one mechanism responsible for these two functions, or are there two separate, domain-specific, visual analyzers?

In support of the notion of separate mechanisms, several dissociations were reported between the orthographic-visual analyzer and the numeric-visual analyzer. Both word reading and number reading involve a character-position encoding process as part of the visual analysis. However, Friedmann, Dotan, and Rahamim (2010) reported 10 individuals who had letter position encoding impairment but whose digit position encoding was normal. Friedmann et al. further showed that even participants with a double deficit (in words and numbers) had different error patterns in words and numbers: letter position errors were more frequent in interior letters than in the exterior letters, whereas digit position errors occurred mostly in the rightmost digits. These findings suggests that the position encoders of letters and digits are separate.

Letter identity dyslexia (sometimes referred to as visual dyslexia), a selective deficit in letter identification, can sometimes affect digit identification too (and even other symbol types, Sinn & Blanken, 1999), but importantly, cases of individuals with a letter identification deficit who showed intact digit identification were reported as well (Crutch & Warrington, 2007; Déjerine, 1892; but see Bub, Arguin, & Lecours, 1993, for a methodological criticism on Déjerine's letter-digit dissociation).

Neglect dyslexia, another disorder that affects the visual processing of character strings, can impair number processing while sparing words (Priftis et al., 2013) or the other way around (Friedmann & Nachman-Katz, 2004; Nachman-Katz & Friedmann, 2008). At the neural level, the word-number separation in visual processing is supported by studies that showed different brain activity patterns following exposure to letters and digits (Abboud, Maidenbaum, Dehaene, & Amedi, 2015; Baker et al., 2007; Grotheer, Herrmann, & Kovacs, 2016; Hannagan et al., 2015; Park, Hebrank, Polk, & Park, 2012; Shum et al., 2013). All this evidence lead to the conclusion that there are separate visual analysis processes for words and numbers.

Dissociations between words and numbers were not yet reported with respect to the structural components of the orthographic/numeric visual analyzers – decimal structure analysis of digit strings and morphological analysis of letter strings.[4] In the present study, we report such dissociation: we show a selective deficit in the decimal structure analysis of number reading, without a corresponding deficit in word reading.

1.2.4.3. Verbal Production of words and numbers

Verbal production of words and numbers is also at least partially separate. Temple (1989) and Marangolo et al. (2004) reported individuals who had impaired number production alongside spared word production, and Bencini et al. (2011) reported the opposite pattern. At the neural level, we are not aware of any brain imaging study that directly compared verbal production of numbers with verbal production of non-number words.

Turning to higher granularity, there are dissociations between the phonological retrieval mechanisms of words and numbers – certain types of aphasia cause phoneme substitutions and omissions in words but not in numbers (Bachoud-Lévi & Dupoux, 2003; Bencini et al., 2011; Cohen et al., 1997; Delazer & Bartha, 2001; Dotan & Friedmann, 2015; Girelli & Delazer, 1999; Marangolo et al., 2004, 2005). This dissociation indicates that words and number words are handled by different sub-processes within the verbal production system. The idea is that for non-number words, the phonological production pathway includes retrieving the word's phonemes from the phonological output lexicon, merging them in the phonological output buffer, and sending the merged word to articulation (Fig. 1). In contrast, number words are not stored in the phonological output lexicon broken into phonemes; rather, they are stored in dedicated phonological stores, where their phonemes are already assembled and ready for articulation (Dotan & Friedmann, 2015). Interestingly, morphological affixes (and function words) are also handled, just like number words, as atomic, already-assembled phonological units. This creates similarities in error patterns between multi-digit numbers and morphologically complex words: impairments at the phonological output buffer stage cause number substitutions and omissions in multi-digit numbers, and similarly, morphological errors – affix omissions and substitutions – in morphologically complex words. This similarity between numbers and morphological affixes supports the homology proposed above (Section 1.2.3) between the structural processing of multi-digit numbers and of morphologically complex words.

An interesting dissociation of syntactic/structural processes in speech production was reported by Marangolo et al. (2004): their patient FA had syntactic errors in numbers (e.g., 5,300 → 500,300) but his word production was spared. A possible explanation of this dissociation is that FA had a selective deficit in the generation of the number word frame, with no corresponding deficit in word production. This would imply separate verbal production mechanisms for words and numbers, at least with respect to structural processing.

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[4] There were also no reports of word-number dissociations with respect to the binding of letters to words – in fact, it is even unknown whether a corresponding digit-to-number binding process exists in the visual analysis of numbers.

Another interesting word-number dissociation was reported by Cipolotti (1995). This dissociation specifically concerns the structural mechanisms of number processing: Cipolotti's patient SF made errors in number reading but his word reading was spared, i.e., he had a deficit in a process that specifically serves number reading. His number reading errors were primarily syntactic, indicating that the impaired, number-specific process was a structural process – one that handles the number's decimal or verbal structure. Based on SF's performance in various tasks, Cipolotti concluded that his deficit was neither in visual analysis nor in verbal production but in the transfer of information between these two stages. This dissociation is the only clear evidence for a selective deficit in a structural component of number reading with spared word reading. Such dissociation pattern is important because it shows that the structural processes involved in number reading are dedicated to numbers and do not serve words. The present study shows another such structural dissociation, in different processes: we report two women with deficits in specific structural processes of number reading, whose word reading is spared. Importantly, to show the dissociation between structural processes in words and numbers, we also examined the participants' structural processes in word reading (i.e., morphological processing), which was not done in most previous studies.

2. Method

2.1. Procedure

The participants were tested in a series of 1- to 2-hour sessions in a quiet room in our lab. In the reading tasks, words or numbers were presented on paper in Arial 16 font with no time limit. An error followed by a self-correction was classified as an error in our coding of responses.

Control participants with outlier error rates were excluded. The threshold for outlier was defined per task as exceeding the 75th percentile of error rates by more than 150% of the inter-quartile distance. Individual participants were compared to control groups using Crawford and Garthwaite's (2002) one-tailed t-test. In cases of a control group ceiling effect (mean error rate $\leq 2\%$), the low variance does not allow for a reliable statistical comparison. In such cases, we set an arbitrary threshold for impaired performance. The threshold was set at 7% errors, in line with the recommendations of Willmes (1990) for analyzing performance in situations of ceiling effects.

2.2. Participants

ED and NL are two sisters with developmental difficulties in number reading. At the time of examination, NL was a 24 year-old B.A. student with 14 years of education, and ED was 31 years old, with an undergraduate degree (15 years of education), working in an administrative job. Both were right handed and had corrected-to-normal vision. Appendix A brings additional background information regarding their phonological short-term memory and writing words to dictation (which were intact) and their multi-digit number writing to dictation, which was impaired. In Dotan and Friedmann (2018) we describe additional aspects of their number reading. Both participants, and all control participants, were native speakers of Hebrew.

3. Number reading: pattern of impairment and locus of deficit

To examine ED's and NL's number reading, and to find out which components of the number reading process were impaired, we assessed their number reading using a series of tasks that tap the numeric-visual analyzer, the verbal production mechanisms, and sub-processes within the two.

3.1. Number reading task

ED and NL read aloud a list of 120 Arabic numbers with 3, 4, 5, or 6 digits. The digit 0 appeared in 63 numbers, and the other numbers contained only the digits 2-9 (the digit 1, which creates the irregularity of x-teen numbers when in the decade position, was not used). The numbers were printed on paper without a comma separator between the hundreds and the thousands digits. ED's and NL's reading was compared with that of 21 Hebrew-speaking control participants (Mean age = 25;5, SD = 2;7; three other control participants were excluded due to outlier error rates).

Table 1. Error percentages in number reading: both participants had many first-digit shifts.

	ED	NL	Control group mean (SD)
All errors	23^{***}	23^{***}	2.8 (1.3)
Decimal shifts	17^{+++}	14^{+++}	1.1 (1.1)
1st-digit shifts	17^{+++}	12^{+++}	1.1 (0.9)

Comparison with the control group: *** $p < .001$

$^{+++}$ Errors ≥ 7%, control group ≤ 2% errors

Both participants had high error rates in number reading (Table 1). The majority of their errors were decimal shifts – producing a number word as if the corresponding digit was in a different decimal position (e.g., 230 → 2030 or 2300 or 203), without errors in the relative order of non-zero digits[5]. Interestingly, most of the decimal shift errors were in the first (leftmost) digits (hereby, first-digit shifts). These first-digit shifts can originate in impaired analysis of the number's structure (its length or its triplet structure) in the numeric-visual analyzer; or in impaired number word frame generation in the verbal production stage (Dotan & Friedmann, 2018). For example, encoding the number 230 as if it had 4 digits may result in saying 2300 or 2030, and incorrect triplet parsing (2,30) may result in saying 2030. To tease apart these different possible loci of impairment in number reading, the numeric-visual analyzer or verbal production, we administered several additional tasks.

3.2. Detecting the origin of first-digit shift errors

To identify the origin of ED's and NL's first-digit shift errors in number reading, we used tasks that examined the processes whose impairment could potentially account for these errors.

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[5] In the literature of symbolic number processing, such errors are described as "syntactic errors". In Dotan and Friedmann (2018) we suggested to further break syntactic errors into types. Decimal shifts are a subset of syntactic errors, where a digit (or number word) changes its decimal position but not its order versus the other digits. Other sub-types of syntactic errors may be, for example, the substitution of a 0 by a non-0 (e.g., 304 → 374).

These processes are the structural analysis in the numeric-visual analyzer – the number length detector and the triplet parsing process, and the structural processing in the verbal production stage – namely, the generation of the number word frame (as described above in Section 1.2.4.3, Fig. 2).

3.2.1. Method

3.2.1.1. Visual input tasks

To examine the numeric-visual analyzer, we used tasks that assess the encoding of the digit identities, the digit order, and the length of the number, without requiring production of verbal numbers.

Same-different decision. The participants saw 240 pairs of numbers of 3-6 digits, and were requested to decide whether the two numbers in each pair were identical or not. The numbers appeared on the screen one after another, each for 1000 ms, with a 500 ms interval between them. There were 120 identical pairs and 120 different pairs. The different pairs included 60 length-differing pairs, in which a number differed from the other one in length, by omitting or adding one digit. To ensure that the participants cannot use digit identity to compensate for a length-encoding deficit, the twot numbers in a length-differing pair always included the same digits in the same order. This was obtained by using numbers in which a single digit was repeated and only one digit was different (e.g., 9949-99499). Additional 60 control pairs differed in the identity of a single digit (e.g., 9929-9959). If a participant has a deficit in the number length encoder in the visual analyzer, she should fail to detect the difference between numbers such as 9949 and 99499. However, other deficits, including impaired triplet parsing in the visual analyzer, should not disrupt the performance in such pairs.

Number matching. The task included 500 numbers, organized in 10 blocks. In each block, the participants saw a sample number and 49 numbers printed under it. They were instructed to circle all numbers that were identical to the sample number. Of the 490 numbers, 191 were identical with the sample, 100 were derived from the sample number by transposing two digits, 100 were derived by adding/deleting a repeated digit (number-length difference), and 99 were derived by substituting one digit. Here too, as in the same-different decision task, the number-length difference did not modify the digit identity or order (e.g., sample: 66676, target: 666766), so a deficit in the number-length encoder in the visual analyzer is the only deficit that should disrupt the performance in the number-length-differing items.

3.2.1.2. Verbal production task

The *Multiplication/division by 10 task* taps the generation of number word frames. The participants saw 28 multiplication-by-10 and 28 division-by-10 problems, in random order (e.g., 3,400 x 10 =). The non-10 operand had 3-5 digits, and only its first two digits were non-zero, so the results had 2-6 digits. The numbers were presented with a comma separator between the hundreds and thousands digits. The participants read aloud each problem and then said its result. The idea is that although the problems were presented visually, the participants said a number other than the one displayed, so the number produced did not arrive directly from the numeric-visual analyzer. Additionally, the presentation of the numbers with commas alleviates the effect of a possible difficulty in triplet parsing. Thus, the task taps production but not visual analysis. Moreover, because they read the numbers in the problem out loud, we could determine that even when they made an error in solving the problem, they still read the numbers correctly: there was no trial in which an erroneous answer was preceded by erroneous reading aloud of the problem. This clearly indicates that the errors in saying the solutions did not originate in impaired visual analysis.

3.2.1.3. Number reading with manipulations

We administered three tasks in which the participants read the same 120 numbers that they had read in the number reading task (Section 3.1). Each of these three tasks differed from the original number reading task in a way that, without changing the target number, should help a participant with a particular visual or verbal deficit, as detailed below. Thus, each task allowed tapping impairments in a specific visual or verbal process. To analyze the effect of the manipulations, the performance in each of these tasks was compared with the participant's performance in standard number reading (Section 3.1) using McNemar test. The manipulations affected only numbers with 4 digits or more, so only these numbers were analyzed and compared versus the standard reading.

Read numbers with comma. The numbers were presented with a comma separator between the thousand and hundred digits – e.g., a number that was presented previously (Section 3.1) as 54321 was now presented as 54,321. The comma separator should help a person with impaired triplet parsing or impaired number-length detector, but should have no effect in case of a verbal production impairment. The reading of the 90 numbers with 4 digits or more was analyzed and compared with the reading of the same number in standard (no-comma) presentation.

Read numbers as triplets. The numbers were visually presented like in Section 3.1 and the manipulation was on the task instructions: the participants were requested to read the number as if it was two separate shorter numbers, saying "and then" between them (instead of the word “thousand”). For example, they had to read the number 54321 as “fifty four and then three hundred and twenty one”. Each of the two shorter numbers is presumably verbally easier than the long number (it has a shorter number word frame), so the manipulation should help a person with a verbal impairment in number word frame generation. In contrast, the manipulation should have no effect on a person with a visual deficit. The participants' reading of all the 90 numbers with 4 digits or more was analyzed and compared with their reading of the same 90 numbers in standard reading.

Read numbers with comma as triplets. In this condition, both manipulations were applied: numbers were presented with comma and read aloud as two shorter numbers.

3.2.2. Results and discussion

NL had many first-digit shift errors in the task that specifically taps verbal production (multiplication/division by 10, Table 2), indicating that at least some of her first-digit shift errors in number reading originated in impaired verbal production. Within verbal production, we diagnosed NL's deficit as located in the generation of number word frames, because this is the only process whose impairment can explain first-digit shift errors. Had her impairment been in another verbal sub-process, we should have observed other error types: impaired phonological retrieval should yield decimal shifts in all decimal positions (e.g., 230 → 203), not only in the first digits, as well as digit substitutions (e.g., 24 → 25); and impaired digit-to-frame binding should yield transpositions or decimal shifts in all positions.

Neither adding a comma separator nor reading the numbers as triplets improved NL's reading (Table 3), but her reading improved when both manipulations were applied in conjunction in the same task. This suggests that she had a double deficit – in visual analysis and in verbal production. Each of the aiding manipulations (comma, triplets) affected only one of the impaired processes, so it did not improve her performance; only applying both manipulations in conjunction helped her.

Two types of specific impairments within visual analysis can potentially account for NL's first-digit shifts as a predominant error type: impaired number-length detection and impaired parsing of digits into triplets. NL's length detection was intact, as demonstrated by her good performance in same-different decision and in number matching (Table 2). Thus, we concluded that within the numeric-visual analyzer, her deficit was in the sub-process that groups digits to triplets. On top of that, she had a deficit in verbal production.

Table 2. Error percentages in number processing tasks. Both participants had high rates of first-digit shift errors in reading numbers.

				Control group		
	Task and type of error	ED	NL	Errors (SD)	N	M Age (SD)
Visual analysis	*Same-different decision*				20	29;6 (7;3)
	Number-length errors	5	0	1.9 (2.4)		
	Digit substitution errors	7^{*}	0	2.3 (2.0)		
	Errors in identical pairs	5	1	2.5 (1.5)		
	Digit order and triplet parsing were not tested in this task.					
	Number matching				20	26;1 (4;4)
	Number-length errors	6	0	0.5 (0.8)		
	Digit order errors	5	0	0.3 (0.6)		
	Digit substitution error	0	0	0.2 (0.4)		
	Errors in identical pairs	2	7	3.1 (2.7)		
	Triplet parsing was not tested in this task.					
Verbal production	*Multiplication/division by 10*				20	27;10 (5;4)
	All errors	5	20^{***}	2.6 (3.0)		
	1st-digit shifts	5	20^{***}	2.0 (2.7)		

Comparison to the control group: * $p \le .05$ *** $p \le .001$

ED did not have many first-digit shift errors in the verbal production task (multiplication/division by 10, Table 2), and reading the numbers as triplets did not significantly reduce her first-digit shifts (Table 3). This indicates that her verbal production was intact, i.e., her first-digit shifts in number reading did not result from a production deficit. In contrast, her number reading was significantly improved by adding the comma separator (Table 3), indicating impaired visual analysis. ED's pattern of results suggests that her first-digit shifts resulted from impaired parsing of numbers into triplets rather than from impaired number-length detection: in the items that specifically tap the number-length detector (the length-differing pairs in the same-different task, and the number-length-error items in the number matching task), her error rates were within the normal range (lower than 7%, which is our impaired-performance threshold given the control group's ceiling effect, see Section 2.1). We therefore concluded that ED's deficit was in the numeric-visual analyzer sub-process that groups digits to triplets.

Table 3. The rates of 1st-digit shift errors in 4-6 digit numbers when reading the same numbers in different modes. Each of the special reading modes was designed to reduce the number of 1st-digit shifts if a participant has a cognitive deficit in a particular structural sub-process: number length encoding or digit parsing in the visual analyzer, and number word frame generation in verbal production.

Taps a deficit in…	Reading mode (task)	ED	NL
(Baseline)	Standard	21	11
Visual analysis	With comma separator	0 ***	9
Verbal production	Read aloud as triplets	13	18
Double deficit (visual & verbal)	With comma separator, as triplets	3 ***	1 ***

Comparison against the standard reading mode (McNemar): *** $p \leq .001$

To summarize, both ED and NL had impaired number reading. Both of them were impaired in the numeric-visual analyzer, in the triplet parsing function of the structural analysis. On top of that, NL was also impaired in the structural-verbal production stage, in the generation of number word frames.

4. Word reading

We now turn to the main question of this study: do these structural components, which were found impaired in our participants' number reading, serve both number reading and word reading? If so, they should affect word reading as well. If, however, our participants show a deficit only in number reading, this would indicate separate processing mechanisms for number and word reading.

To answer this question, we examined ED's and NL's word reading using several tasks. We aimed to examine whether a specific dissociation exists between homologous functions of number reading and word reading. Because both ED and NL were impaired in the numeric-visual analyzer, we specifically examined their visual analysis in word reading. For this aim, we tested their ability to identify letters, encode their positions within the word, and bind letters to the word in which they appeared. Furthermore, because ED's and NL's impairment in the visual analysis of numbers was in the structural analysis component, we sought for parallel structural analyses in word reading. We suggest that the analysis of the morphological structure of words is the closest homologue to the analysis of the decimal structure of multi-digit numbers, and we therefore included tasks that tap the morphological structure functions of the orthographic-visual analyzer.

Because NL was impaired also in verbal production of numbers, we also examined the participants' verbal production of words. Here too NL's deficit in numbers was in structural processes (number word frame generation), so we used word production tasks that tap structural processes, in particular the oral production of morphologically complex words.

4.1. Orthographic-visual analyzer

To examine ED's and NL's visual analyzer in reading words, we used oral reading of words, which relies on the orthographic-visual analyzer as well as on verbal production. We also used a task that required silent reading, which relies on the orthographic-visual analyzer but not on verbal production.

4.1.1. *Method*

ED and NL read aloud a total of 928 words and 40 nonwords[6], administered as several tests. First, we used the screening tasks from the TILTAN battery for the identification of subtypes of dyslexia (Friedmann & Gvion, 2003), which includes three subtests: oral reading of 136 single words, 30 word pairs, and 40 nonwords. These tests contain words of various types (in random order), which can reveal different types of dyslexia (and, specifically for our purpose in the current study, can assess the performance of the various components of the word reading process):

- Irregular words and potentiophones[7] for the identification of surface dyslexia and for assessment of the lexical route.
- Nonwords for the identification of phonological and deep dyslexia and for assessment of the sub-lexical route.
- Morphologically complex words for identifying deep dyslexia, deficits in the orthographic input buffer or the phonological output buffer, and for the assessment of morphological decomposition and composition (Cohen et al., 1994; Dotan & Friedmann, 2015; Job & Sartori, 1984; Reznick & Friedmann, 2009, 2015; Stuart & Howard, 1995; Temple, 2003).
- Words (and nonwords) that can be read as other words by neglecting one side of the word, for the identification of neglect dyslexia (Friedmann & Nachman-Katz, 2004; Haywood & Coltheart, 2001; Patterson & Wilson, 1990; Reznick & Friedmann, 2015).
- Words with many orthographic neighbors for visual dyslexia (Cuetos & Ellis, 1999; Friedmann et al., 2012; Lambon-Ralph & Ellis, 1997; Marshall & Newcombe, 1973).
- Word pairs in which between-word migration creates other existing words, for the identification of attentional dyslexia (Friedmann, Kerbel, et al., 2010; Humphreys & Mayall, 2001; Mayall & Humphreys, 2002; Shallice & Warrington, 1977).

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[6] When reading nonwords in Hebrew, some letter strings can be correctly converted to phonological format in more than one way, and we accepted all of them as correct answers. For example, the nonword שיגזון can be read as /shigazon/, /shigzon/, or /shigezon/. This ambiguity results from the Hebrew orthography being under-specified with respect to vowels.

[7] *Potentiophones* are pairs of words that contain homophonic letters (and are usually underspecified for vowels). If read solely via the sublexical route (grapheme-to-phoneme conversion), one word can be read aloud instead of the other. For example, the English word *now*, when read aloud via the sublexical route, may erroneously be pronounced like the words *no* and *know* (Friedmann & Lukov, 2008).

- Words that allow for vowel errors, for the identification of vowel letter dyslexia (Khentov-Krauss & Friedmann, 2011, in press).
- Migratable words and nonwords (words or nonwords in which a transposition of interior letters yields an existing word), for the identification of letter position dyslexia (Friedmann, Dotan, & Rahamim, 2010; Friedmann & Gvion, 2001; Friedmann & Haddad-Hanna, 2012; Friedmann & Rahamim, 2007; Peressotti & Grainger, 1995).

ED and NL read two additional lists of words. One list included 232 migratable words, to tap letter position encoding. Another list was a test designed to assess the effect of morphological structure of the target word on letter transpositions (Friedmann et al., 2015). This list included 500 migratable words, out of which 402 were morphologically complex.

On top of the reading aloud tasks, ED and NL also performed two lexical decision tasks, which required orthographic-visual analysis but did not involve verbal production. One task focused on letter position encoding – it included 30 words, 15 migratable nonwords, and 15 non-migratable nonwords. Another task focused on morphological encoding – it included 45 words and 60 nonwords, all morphologically complex. In both tasks, words were printed on paper and the participants were asked to circle the existing words.

4.1.2. Results

In all the word reading tasks, both ED and NL performed very well, and their error rates were within the norm for their age (Table 4). Their performance in the word reading task, in which they read 136 words, was significantly better than their number reading task described in Section 3.1 (Fisher's exact, two-tailed $p < .001$; Cohen's h = 0.7, i.e., a large-medium effect size). This forms a clear dissociation between their visual analysis of digit strings, which was impaired, and their visual analysis of letter strings, which was spared. The dissociation between the word reading and number reading tasks meets the criteria for classical dissociation (Crawford, Garthwaite, & Gray, 2003), with the exception that due to the nature of our measures, the comparison between the two tasks was not done with t-test but with two-tailed Fisher's exact test. Furthermore, the dissociation was demonstrated both by tasks that specifically tapped the visual analysis stage and by tasks that required oral reading.

ED's and NL's success in all word reading tasks clearly shows that their morphological processing in word reading was intact. As a Semitic language, Hebrew has a rich morphology – all verbs and most nouns and adjectives in Hebrew are constructed from a root and a morphological template and/or inflection. Hebrew also has deep orthography, including many degrees of freedom, because vowels are only partially represented in the orthographic forms, stress is not represented at all, and 13 out of the 22 letters can be converted to more than one phoneme (Friedmann & Lukov, 2008). Hebrew's deep morphology and deep orthography make it virtually impossible to read morphologically complex words correctly without processing their morphological structure. Still, ED and NL were able to do this easily: each of them read aloud 712 morphologically complex words, and they made no more errors on these words than the control participants.

This good morphological processing in word reading stands in marked contrast to ED's and NL's impairments in homologous structural processes in number reading (Section 3): both had an impairment the numeric-visual analyzer's sub-process that groups digits to triplets, and

NL had an additional impairment in the generation of number word frames. Our findings therefore not only show a general dissociation between number reading and word reading, and between visual processes in number and word reading, but also a more specific dissociation – between structural processes in number reading (triplet parsing, number word frame generation), which are impaired, and structural processes in word reading, which are spared.

Table 4. Error percentages in tasks that tap orthographic-visual analysis and verbal production of words. Both participants performed well in all tasks – their error rates were not significantly higher than the controls.

	Task	Total no. of items (and the no. of morphologically complex words)	ED	NL	Control group		
					Errors (SD)	n	Age (SD)
Reading	Read words	136 (76)	1	2	1.7 (1.5)	372	28;7 (7;0)
	Read nonwords	40	0	8	4.1 (4.2)	372	28;7 (7;0)
	Read word pairs	30x2 (52)	0	3	2.5 (2.4)	372	28;7 (7;0)
	Read migratable words	232 (182)	2	1	2.4 (1.8)	192	18+ [a]
	Read morphologically complex words	500 (402)	2	2	1.8 (0.4)	10	30;5 (13)
Visual	Lexical decision						
	Migratable	60 (11)	0	3	0.3 (0.6)	19	18+ [a]
	Morphologically complex	105 (45)	0	0	1.0 (0.9)	24	28;8 (4;2)
Verbal	Picture naming	100 (27)	2	3	2.3 (1.7)	87	20-40
	Verb elicitation	24 (24)	0	0	0.2 (0.6)	18	38;11 (14;5)
	Nonword repetition	48	2	2	4.4 (3.5)	20	31;2 (8;9)

[a] No age information for this control group, but all control participants were over 18 years old.

In other aspects, the structural processes in number reading are also homologous to processes that handle the orthographic structure of the word with respect to its CV (consonant-vowel) structure. These orthographic structural processes too were spared in ED and NL's reading: virtually all the 928 words that they read included both consonants and vowels, and they read them well, indicating good processing of consonants and vowels, in contrast to their structural impairment in number reading.

4.2. *Verbal production of words*

4.2.1. Method

Because NL had a deficit in the verbal production mechanism of numbers, we also directly examined her verbal production of words. Her good oral reading of words was already a strong indication that her verbal production was intact. To examine it further we administered three tasks that involve verbal production without reading. In the picture naming task (SHEMESH test, Biran & Friedmann, 2004), the participants were presented with 100 object pictures and asked to retrieve their names. In the nonword repetition task (from the BLIP battery, Friedmann, 2003), they repeated 48 nonwords with 1-4 syllables. In the inflected verb elicitation task, they had to orally complete a missing verb in a sentence by inflecting the verb (BAFLA, Friedmann, 1998). This third task was used to test directly their production of morphologically complex words.

4.2.2. Results

ED and NL performed well in the word production tasks (Table 4). These results show another dissociation between numbers and words: NL had a deficit in a structural process in number production (the generation of number word frames), but she showed good production of words, even in the task that taps structural (morphological) processing. This provides another specific dissociation, this time between the structural verbal processing of numbers and words.

5. Discussion

5.1. A dissociation of structural processes

ED and NL showed a general word-number dissociation: their number reading was impaired but their word reading was spared. Our aim, however, was to go beyond this general level, and focus on parallel processes in number and word reading and see whether they are dissociable. First, because ED and NL had a deficit in the visual analysis processes in number reading, we examined their visual analysis processes in word reading. This examination yielded a specific dissociation between the visual analysis of numbers, which was impaired, and the visual analysis of words, which was spared. We then took a step further in the granularity level and examined the specific process within the visual analysis of numbers that was impaired for ED and NL. Their number-processing impairments were in structural processes: parsing a digit string to triplets in the visual analyzer, and generating the number word frame in verbal production.

To examine the dissociation that relates to their impaired structural processes of number reading, we looked for the homologous mechanism that processes a word’s structure. We propose that processing the number’s structure is homologous to the morphological decomposition and composition of morphologically complex words. These morphological processes in word reading were intact for both participants, as demonstrated by their success in several tasks that required morphological processing of words. A dissociation between these specific structural processes in number and word reading was not yet reported in previous studies. As far as we know, there is only one previous report of word-number dissociation in specific structural processes (Cipolotti, 1995, patient SF). Taken together, the cases of ED, NL, and SF indicate that the structural processing of numbers is done by dedicated processes, which do not serve word reading.

A further dissociation we found related to the orthographic structure of words and numbers. The structure of multi-digit numbers also involves the analysis of the position of zeros with respect to other digits. The parallel orthographic structure of words in this respect is the CV (consonant-vowel structure of the word). Such putative homology also results in a dissociation between words and numbers: ED and NL managed to read words perfectly well, including good processing of consonants and vowels, in spite of impaired processing of the structure of numbers.

Finally, the verbal structure of multi-digit numbers is also homologous in other respects to the syntactic structure of sentences. Verbal numbers contain multiple words, organized in a certain structure, and include function words, similarly to sentences. Moreover, a number's verbal structure may be internally represented in a hierarchical manner, resembling the internal representation of the syntax of sentences (Dotan & Friedmann, 2018). Examining this possibility would require to compare the ability to process a number's verbal structure and the ability to process the syntax of a sentence. Such a comparison was beyond the scope of the present study, but preliminary data from our lab suggests that structural processing of verbal numbers dissociates from sentence processing as well.

5.2. *Word reading and number reading: two separate cognitive pathways*

Both ED and NL were impaired in the structural sub-processes in the visual analysis of digit strings, but not in the structural processes in the visual analysis of words. NL was additionally impaired in the structural processes of verbal number production, but not in word and nonword production. ED and NL therefore join the small group of reported cases with number-specific reading deficits, which do not affect word reading (Basso & Beschin, 2000; Cipolotti, 1995; Cipolotti et al., 1995; Marangolo et al., 2004; Priftis et al., 2013; Temple, 1989).

Our findings, in conjunction with previous reports on word-number dissociations, indicate that almost all the sub-processes of number reading are dedicated to numbers and do not serve word reading. In the visual analysis stage, position encoding is separate for letters and digits (Friedmann, Dotan, & Rahamim, 2010), and so are digit identity encoding (Abboud et al., 2015; Baker et al., 2007; Grotheer et al., 2016; Hannagan et al., 2015; Park et al., 2012; Shum et al., 2013) and triplet parsing (ED, NL). In verbal production, the generation of number word frames is a number-specific process (NL), and phonological retrieval is done in different ways for number words and other words (Bachoud-Lévi & Dupoux, 2003; Bencini et al., 2011; Cohen et al., 1997; Dotan & Friedmann, 2015; Marangolo et al., 2004, 2005).

The only number-processing components for which dissociations with word processing have not yet been studied are the numeric-visual analyzer sub-processes that encode the 0 positions and the number length. Future studies may examine whether these processes too dissociate from the homologous processes in the visual analysis of words: the encoding of word length (homologous to the number length) and the detection of vowel letters (homologous to the detection of 0's in a number, see Khentov-Krauss & Friedmann, 2018, for vowel-specific deficit in reading).

From a clinical perspective, our findings indicate that word reading disorders (dyslexia) should be treated as a separate clinical situation from number reading disorders. We therefore propose to refer to number reading disorders using a separate term – "dysnumeria". A person may have only dyslexia for words, only dysnumeria for numbers, or for both. The two types of disorders should be assessed separately for each individual – one cannot automatically conclude from number reading to word reading or vice versa. Similarly, different treatment methods may apply to the reading of words and numbers – we cannot make the assumption that treating one would generalize to the other. The assessment tasks we have described here, some of which are completely novel, may serve for the clinical assessment of the various types of dysnumeria (for more details on assessment of dysnumeria, see Dotan & Friedmann, 2018).

5.3. Differences and similarities between the reading mechanisms of words and numbers

Having established that word reading and number reading are done in separate cognitive pathways, we now turn to examining the similarities and differences between these pathways.

5.3.1. Mental lexicons

One important difference between words and numbers is the existence of lexicons. Word reading heavily relies on lexical knowledge, stored in orthographic and phonological lexicons. Conversely, at least for the majority of numbers, no lexicons are involved in number reading, except the knowledge of single digits and the phonological storage of single number words (e.g., /two/, /eighty/, /thirteen/, /hundred/, and even compound words such as the French /quatre-vingt/, 80). Still, an extreme assumption, according to which number reading involves no lexical knowledge whatsoever, is apparently incorrect: at least some multi-digit numbers, those that have a particular meaning (year of birth, car model, etc.), may be stored and identified as whole lexical units. Such putative "numbers lexicon" may be the element that allows some aphasic patients to read familiar numbers even when their number-reading pathway is impaired (Cohen et al., 1994; Delazer & Girelli, 1997).

5.3.2. Letter-to-word binding

Another potential difference between word reading and number reading concerns the way letters or digits are associated with the multi-character string to which they belong. When reading words, the visual orthographic-analyzer has a dedicated process that binds each letter to the appropriate word (Coltheart, 1981; Ellis, 1993; Ellis & Young, 1996). Malfunctions of this process give rise to migrations of letters between words, e.g., reading "**r**ear **d**ock" as "**d**ear **r**ock" – a situation known as attentional dyslexia (Friedmann, Kerbel, & Shvimer, 2010; Humphreys & Mayall, 2001; Saffran & Coslett, 1996). An open question is whether a homologous digit-to-number binding process exists in number reading. It is also an open question whether, if such a digit-to-number binding function does exist, it is the one and the same with the letter-to-word binding function that applies in word reading. Preliminary data from our lab indicate that digit-to-number binding can be intact even for individuals with attentional dyslexia, whose letter-to-word binding is impaired (Lukov & Friedmann, unpublished data).

5.3.3. Structural (syntactic) processing

An important point that stands out from the comparison between word reading and number reading is the role of structural processing. For words as well as for numbers, the structure of the character string (morphological or decimal) is extracted during the early stage of visual analysis (Beyersmann et al., 2011; Dotan & Friedmann, 2018; Longtin & Meunier, 2005; McCormick et al., 2008, 2009; Rastle et al., 2004; Reznick & Friedmann, 2015; Taft & Forster, 1975). Similarly, for words and numbers alike, the structure of the verbal stimulus is encoded throughout the verbal production stage, even in the latest stages (the phonological output buffer, Dotan & Friedmann, 2015, 2018). This role of structural processing suggests that reading is not a simple mechanism that merely scans a series of characters in visual input and processes a series of phonemes in verbal output. Rather, reading has dedicated processes to represent visual and verbal structures, and these processes are tailored to the type of stimulus being processed – words or numbers.

5.4. Specialized pathways for reading words and reading numbers: Why?

Why does our cognitive system allocate two separate processing pathways to words and numbers, two cultural inventions that are very recent in evolutionary terms? Dehaene, Amedi, and collaborators (Abboud et al., 2015; Hannagan et al., 2015) considered this question with respect to the mechanisms of visual analysis of words and numbers which, as they showed, are implemented in different brain areas – the so-called visual word form area (VWFA) and visual number form area (VNFA). They pointed out that the reason for this neural separation is unlikely to be the visual properties of letters versus digits, because letters and digits are visually quite similar (in their experiments, the stimuli were even identical). They proposed that the reason for the neural separation between the VWFA and the VNFA is the connectivity patterns of these brain areas with the rest of the brain, in particular with the regions that make use of the parsed visual information. The VWFA has better connectivity with language areas, which require the parsed letters information, whereas the VNFA has better connectivity with quantity representation areas (IPS), which require the parsed digits information. The architecture we proposed here, where reading is dominated by structural processing, offers a complementary explanation for the separation of words and numbers. Although the visual properties of letters and digits are quite similar to each other, the structural properties of letter strings and digit strings are very different from each other: the decimal structure of digits is completely different from the morphological structure of words. Consequently, a dedicated visual analysis process that extracts the morphological structure of words could be very different from a dedicated visual analysis process that extracts the decimal structure of numbers. These differences may motivate the allocation of different cognitive and neural circuits to the visual analysis of words and numbers. When a processing stage is structure-insensitive, it may be shared for words and numbers, as seems to be the case for the early processes that precede the numeric/orthographic visual analyzers (McCloskey & Schubert, 2014) and for post-phonological-retrieval processes (Shalev et al., 2014). The structural differences merely provide motivation for separating words from numbers – they do not necessarily favor the allocation of word and number processing to specific brain regions. The allocation of a specific cognitive function to a specific brain region may be driven by other factors, such as neural connectivity patterns.

One thing is clear: the specialization of different cognitive processes to words and numbers is quite rigid. The growing number of word-number dissociations demonstrates that at least in some cases, a well-functioning processing of words cannot overtake an impaired processing of numbers, and vice versa, even when the impairment is developmental and presumably existed from birth. This rigidity of word-number separation accords with the rigidity we observe within each of these domains: an intact process is sometimes unable to compensate for an impaired process, even when two processes encode information that appears to be redundant (Dotan & Friedmann, 2018). Future studies may elaborate further on the cognitive and neural factors that drive the development of this neural and cognitive specialization.

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Appendix A. Additional background information for the participants: Memory, number writing

Table A.1. Performance in memory and number-writing tasks.

	ED	NL
Memory span		
Digit (free recall)	5^+	5^+
Digit (matching)	7	7
Word (free recall)	4½	5
Word (matching)	7	7
Dictation (% errors)		
Writing 50 words	2%	2%
Writing 50 numbers	2%	20%

Comparison to control group: $^+$ one-tailed $p < .1$

The two participants showed normal-level performance in phonological short-term memory tasks (FriGvi battery, Friedmann & Gvion, 2002; Gvion & Friedmann, 2012) and in writing words to dictation (TILTAN battery, Friedmann, Gvion, & Yachini, 2007).

In writing numbers (digit strings) to dictation (tested with the MAYIM battery, Dotan & Friedmann, 2014), NL had many errors, all of which were syntactic (number length, the position of the digit 0). ED did not have many errors, but she often hesitated when writing the digit 0, suggesting a difficulty similar to NL's.