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Research report

A cognitive model for multidigit number reading: Inferences from individuals with selective impairments

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ABSTRACT

We propose a detailed cognitive model of multi-digit number reading. The model postulates separate processes for visual analysis of the digit string and for oral production of the verbal number. Within visual analysis, separate sub-processes encode the digit identities and the digit order, and additional sub-processes encode the number's decimal structure: its length, the positions of 0, and the way it is parsed into triplets (e.g., 314987 → 314,987). Verbal production consists of a process that generates the verbal structure of the number, and another process that retrieves the phonological forms of each number word. The verbal number structure is first encoded in a tree-like structure, similarly to syntactic trees of sentences, and then linearized to a sequence of number-word specifiers. This model is based on an investigation of the number processing abilities of seven individuals with different selective deficits in number reading. We report participants with impairment in specific sub-processes of the visual analysis of digit strings – in encoding the digit order, in encoding the number length, or in parsing the digit string to triplets. Other participants were impaired in verbal production, making errors in the number structure (shifts of digits to another decimal position, e.g., 3,040 → 30,004). Their selective deficits yielded several dissociations: first, we found a double dissociation between visual analysis deficits and verbal production deficits. Second, several dissociations were found within visual analysis: a double dissociation between errors in digit order and errors in the number length; a dissociation between order/length errors and errors in parsing the digit string into triplets; and a dissociation between the processing of different digits – impaired order encoding of the digits 2–9, without errors in the 0 position. Third, within verbal production, a dissociation was found between digit shifts and substitutions of number words. A selective deficit in any of the processes described by the model would cause difficulties in number reading, which we propose to term "dysnumeria".

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1. Introduction

Number reading is a complex cognitive operation involving several different sub-processes, each of which can be impaired and cause a different type of reading errors (Basso & Beschin, 2000; Cappelletti, Kopelman, Morton, & Butterworth, 2005; Cipolotti & Butterworth, 1995; Cipolotti, Warrington, & Butterworth, 1995; Cohen, Verstichel, & Dehaene, 1997; Dehaene, Piazza, Pinel, & Cohen, 2003; Delazer & Bartha, 2001; Deloche & Willmes, 2000; Dotan & Friedmann, 2015; Friedmann, Dotan, & Rahamim, 2010; McCloskey, Caramazza, & Basili, 1985; McCloskey, Sokol, & Goodman, 1986; McCloskey, Sokol, Caramazza, & Goodman-Schulman, 1990; Moura et al., 2013; Noël & Seron, 1993; Starrfelt & Behrmann, 2011; Starrfelt, Habekost, & Gerlach, 2010; Temple, 1989). In the present study, we propose a detailed model of how these cognitive mechanisms of number reading operate.

In doing so, we draw inspiration from models of word reading, another complex and potentially-similar cognitive function. Like number reading, word reading also involves a variety of processes: visually analyzing the sequence of letters, accessing the appropriate entries in orthographic, phonological, and semantic mental lexicons, generating the phonological output, and articulation. After several decades of research, we now have a cognitive model with detailed specification of the processes involved in word reading and of the flow of information among these processes (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Ellis & Young, 1996; Ellis, 1993; Friedmann & Coltheart, in press; Friedmann & Gvion, 2001; Humphreys, Evett, & Quinlan, 1990; Marshall & Newcombe, 1973; Patterson & Shewell, 1987; Shallice, 1988). This model turned out to be invaluable in several ways. From a theoretical point of view, an accurate model of word reading allows for better understanding of the reading mechanisms, and enables detailed investigation of other language processes such as morphology and lexical retrieval (Biran & Friedmann, 2012; Dotan & Friedmann, 2015; Friedmann, Biran, & Dotan, 2013; Funnell, 1983; Gvion & Friedmann, 2016; Job & Sartori, 1984; Reznick & Friedmann, 2009, 2015). From a clinical point of view, such a detailed model improves our ability to identify specific impairments in word reading, to learn about their characteristics, and consequently to diagnose and treat individuals with such impairments (Castles & Friedmann, 2014; Colenbrander, Nickels, & Kohnen, 2011; Coltheart & Kohnen, 2012; Friedmann & Coltheart, 2017; Friedmann & Gvion, 2001; Friedmann et al., 2013; Marshall & Newcombe, 1973; Nickels, 1997; Nickels, Rapp, & Kohnen, 2015; Rapp, 2005; Temple, 2006).

The cognitive model of word reading could not have been as useful had it not been very explicit in terms of information processing: the model accurately describes the function of each cognitive sub-process involved in reading, and the kind of information transferred between these processes, in a manner detailed enough to allow for computational simulation (Coltheart et al., 2001). This high level of granularity is what allows characterizing the interaction between reading and other language processes, and makes it possible to identify specific cognitive disorders in specific processing stages.

The reading of numbers (such as "256") is implemented, at least in part, by separate mechanisms than the word reading mechanisms (Abboud, Maidenbaum, Dehaene, & Amedi, 2015; Friedmann, Dotan, & Rahamim, 2010; Hannagan, Amedi, Cohen, Dehaene-Lambertz, & Dehaene, 2015; Shum et al., 2013; for a review, see Dotan & Friedmann, 2018). However, number reading has not been investigated as much as word reading, and less is known about it. The present study aims to fill this gap.

1.1. *Existing models of number reading*

1.1.1. *The triple code model*

During the 1990's, there was much debate about the representation of symbolic numbers and the transcoding processes that convert between these representations (Cipolotti & Butterworth, 1995; Cipolotti et al., 1995; Cohen & Dehaene, 2000; Dehaene & Cohen, 1997; McCloskey, 1992; McCloskey et al., 1990, 1986; Sokol, McCloskey, Cohen, & Aliminosa, 1991). At present, a widely accepted model is the triple-code model of number processing (Dehaene & Cohen, 1995; Dehaene, 1992; Dehaene et al., 2003), which holds that separate cognitive and neural circuits represent numbers as sequences of digits, as verbal number words, and as quantities. With respect to number reading, the triple-code model postulates that the visual parsing of digital numbers and the verbal production of number words are handled by separate processes, connected by a direct digit-to-verbal transcoding pathway that is at least partially separate from the access to number semantics. Indeed, several studies have shown that the visual analysis of numbers can be selectively impaired (Cohen & Dehaene, 1995; Friedmann, Dotan, & Rahamim, 2010; McCloskey et al., 1986; Noël & Seron, 1993), and so can the verbal production of numbers (Benson & Denckla, 1969; Cohen et al., 1997; Delazer & Bartha, 2001; Dotan & Friedmann, 2015; Dotan, Friedmann, & Dehaene, 2014; Marangolo, Nasti, & Zorzi, 2004; Marangolo, Piras, & Fias, 2005).

1.1.2. *McCloskey's number reading model*

The triple-code model, as well as many of the above studies, characterized the different number representations and transcoding pathways. Other studies, though fewer, were specifically concerned with offering a detailed cognitive model of number reading. Michael McCloskey and his colleagues (McCloskey, 1992; McCloskey et al., 1986) proposed a model where number reading – transcoding a digit string into number words – is mediated by a central semantic representation, which essentially reflects the number's decimal structure (e.g., $2{,}031 = 2 \times 10^3 + 0 \times 10^2 + 3 \times 10^1 + 1 \times 10^0$). Their model postulates that converting this representation to number words begins by creating a *syntactic frame*, which reflects the verbal structure of a number with a given number of digits – e.g., for 4-digit numbers, the syntactic frame is *[_:ones] [thousand:multiplier] [_:ones] [hundred:multiplier] [_:tens] [_:ones]* (the [_:] notation – [_:ones], [_:tens] – represents placeholders for a number word of the corresponding lexical class[1]). The

[1] McCloskey and his colleagues experimented in English and mentioned ones, teens and tens as lexical classes for words. The specific lexical classes may depend on the characteristics of verbal numbers in a specific language. Our study was conducted in Hebrew, in which the number words for hundreds and thousands often introduce some verbal irregularity and may therefore be lexicalized. This would result in hundreds and thousands as two additional lexical classes. However, this question – whether hundreds and thousands are indeed lexical classes in Hebrew – was not in the scope of the present study.

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