CORTEX 59 (2014) 62–73

Available online at www.sciencedirect.com

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Journal homepage: www.elsevier.com/locate/cortex

Breaking down number syntax: Spared comprehension of multi-digit numbers in a patient with impaired digit-to-word conversion

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ARTICLE INFO

Article history:
Received 11 February 2014
Reviewed 9 April 2014
Revised 3 July 2014
Accepted 14 July 2014
Action editor Roberto Cubelli
Published online 22 July 2014

Keywords:
Number representation
Number syntax
Two-digit numbers
Holistic processing
Arithmetic

ABSTRACT

Can the meaning of two-digit Arabic numbers be accessed independently of their verbal-phonological representations? To answer this question we explored the number processing of ZN, an aphasic patient with a syntactic deficit in digit-to-verbal transcoding, who could hardly read aloud two-digit numbers, but could read them as single digits ("four, two"). Neuropsychological examination showed that ZN's deficit was neither in the digit input nor in the phonological output processes, as he could copy and repeat two-digit numbers. His deficit thus lied in a central process that converts digits to abstract number words and sends this information to phonological retrieval processes. Crucially, in spite of this deficit in number transcoding, ZN's two-digit comprehension was spared in several ways: (1) he could calculate two-digit additions; (2) he showed good performance in a two-digit comparison task, and a continuous distance effect; and (3) his performance in a task of mapping numbers to positions on an unmarked number line showed a logarithmic (nonlinear) factor, indicating that he represented two-digit Arabic numbers as holistic two-digit quantities. Thus, at least these aspects of number comprehension can be performed without converting the two-digit number from digits to verbal representation.

1. Introduction

Benjamin Lee Whorf suggested that language lies at the core of human thought and shapes our concepts (Whorf, 1940). In the domain of arithmetic, this view has been explicitly refuted by showing that a broad array of numerical abilities are spontaneously present even without verbal representation of numbers. This has been demonstrated in animals, preverbal infants, and adults from language communities with a reduced lexicon of number words (Brannon & Terrace, 2000; Dehaene, Izard, Spelke, & Pica, 2008; Dehaene, Molko, Cohen, & Wilson, 2004; Feigenson, Dehaene, & Spelke, 2004; Hauser, Carey, & Hauser, 2000; Nieder & Dehaene, 2009; Viswanathan &

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http://dx.doi.org/10.1016/j.cortex.2014.07.005
0010-9452/

Nieder, 2013). Yet a narrower hypothesis may still be tenable, according to which some higher mathematical abilities are tightly coupled with language: a specifically human recursive computation mechanism may underlie syntactic processes, not only in language, but in other cognitive processes, including the way we represent multi-digit numbers and mathematical expressions (Hauser, Chomsky, & Fitch, 2002; Houdé & Tzourio-Mazoyer, 2003). Even this view of "global syntax", however, is challenged by certain findings: brain areas and functional processes that characterize language syntax are dissociable from those that support many combinatorial mathematical processes, including the processing of algebraic operations (Monti, Parsons, & Osherson, 2012) and mathematical expressions (Maruyama, Pallier, Jobert, Sigman, & Dehaene, 2012), multi-digit number naming (Brysbaert, Fias, & Noël, 1998), transcoding, and multi-digit calculation (Varley, Klessinger, Romanowski, & Siegal, 2005).

The present study aims to further probe this issue by analyzing dissociations between different syntactic processes within the domain of number cognition in an aphasic patient with impaired conversion of Arabic numbers to words. Specifically, we asked whether the meaning of two-digit Arabic numbers can be accessed independently of their verbal representations when the syntactic mechanisms converting numbers to words are impaired. Our goal is to examine in detail the locus and nature of the patient's impairment in transcoding, and to evaluate his number meaning abilities and syntactic processes of number comprehension using various tasks.

Numbers have three distinct representations: they can be coded in digits as Arabic numerals (68), as number words (sixty-eight), or as quantities, the dominant "meaning" of the number. These different cognitive representations are dissociable (Gordon, 2004; Lemer, Dehaene, Spelke, & Cohen, 2003), can be selectively impaired (Cohen & Dehaene, 2000), and are implemented in different brain areas (Dehaene, Piazza, Pinel, & Cohen, 2003). However, these representations are tightly related: symbolic representations of numbers (words, digits) are associated with the corresponding quantities, which can be represented spatially along a left-to-right mental number line (Dehaene, Bossini, & Giraux, 1993; Loetscher, Bockisch, Nicholls, & Brugger, 2010; Moyer & Landauer, 1967; Ruiz Fernández, Rahona, Hervás, Vázquez, & Ulrich, 2011; Shaki, Fischer, & Petrusic, 2009).

Multi-digit Arabic numerals enter into several types of internal conversion processes. Converting multi-digit Arabic numbers to number words is a syntactic process that requires encoding the relative positions of the digits according to the base-10 system, converting each digit to a word according to its position, and combining the words, sometimes with the addition of coordination markers ("and"). This syntactic subprocess can be selectively impaired (Cipolotti, 1995; Noël & Seron, 1993). But multi-digit Arabic numbers can also be quickly converted into the corresponding quantity (Dehaene, Dupoux, & Mehler, 1990; Dotan & Dehaene, 2013; Reynvoet & Brysbaert, 1999). Computing the quantity associated with an Arabic multi-digit number requires encoding the relative positions of the digits and combining their quantities according to the base-10 principles. Thus, syntactic operations are required when converting multi-digit Arabic numerals either to verbal number words or to quantities. Is a single syntactic process involved in both conversion processes? The present study addresses one aspect of this question: we asked whether the conversion of a two-digit Arabic number into a quantity can be spared when the syntactic operation involved in forming a verbal representation of the number is impaired.

The triple-code model of number processing (Dehaene, 1992; Dehaene & Cohen, 1995) predicts that there is a direct conversion route from Arabic inputs to the quantity representation, independent of the Arabic-to-verbal route. However, the verbal representation of numbers is also thought to play a crucial role even in tasks that do not necessarily involve overt comprehension and production of verbal numbers, e.g., memorization of arithmetic facts (Cohen & Dehaene, 2000; Dehaene, 1992; Dehaene & Cohen, 1997). The relation between verbal representations and quantity is sometimes surprisingly complex, to the extent that quantity encoding may be affected by the language in which a verbal number is presented, even in the same person: Dehaene et al. (2008) investigated individuals from an Amazonian culture with little or no formal mathematical education, and found that their quantity processing showed a more linear pattern when numbers were presented in a Western second language (Portuguese) than in their native tongue, Mundurucu, where numerals yielded a more logarithmic pattern.

To separate these two possibilities, and probe whether Arabic-to-quantity conversion makes use of a syntactic process that is also needed for Arabic-to-verbal conversion, we examined the various number abilities of ZN, an aphasic patient who has a selective deficit in verbal number production. This deficit prevents him from converting multi-digit numbers into verbal-phonological forms, and renders him almost completely unable to say them aloud. We tested whether, in spite of this deficit, he can encode the holistic quantity of two-digit Arabic numbers.

Another question addressed in this study is whether multi-digit addition depends upon verbal-phonological forms of number words. Rote knowledge of arithmetic facts relies on the verbal representation of numbers (Cohen & Dehaene, 2000; Dehaene, 1992; Dehaene & Cohen, 1997; Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999). Multi-digit addition too can be affected by verbal factors such as the grammatical structure of number words (Colomé, Laka, & Sebastián-Gallés, 2010), though not always (Brysbaert et al., 1998). Phonological representations may be involved in multi-digit addition, but are probably not necessary for it (Klessinger, Szczerbinski, & Varley, 2012). The present case study of ZN extends Klessinger et al.'s conclusions by examining a dissociation between multi-digit addition and the verbal representation of numbers: we tested whether ZN could solve addition problems that involve two-digit numbers in spite of his severe impairment in the conversion of Arabic numbers to verbal representation.

2. Case description

2.1. Overview

ZN, a 73-years-old man, used to work as an engineer, a job that involved a lot of number processing. When he was 72