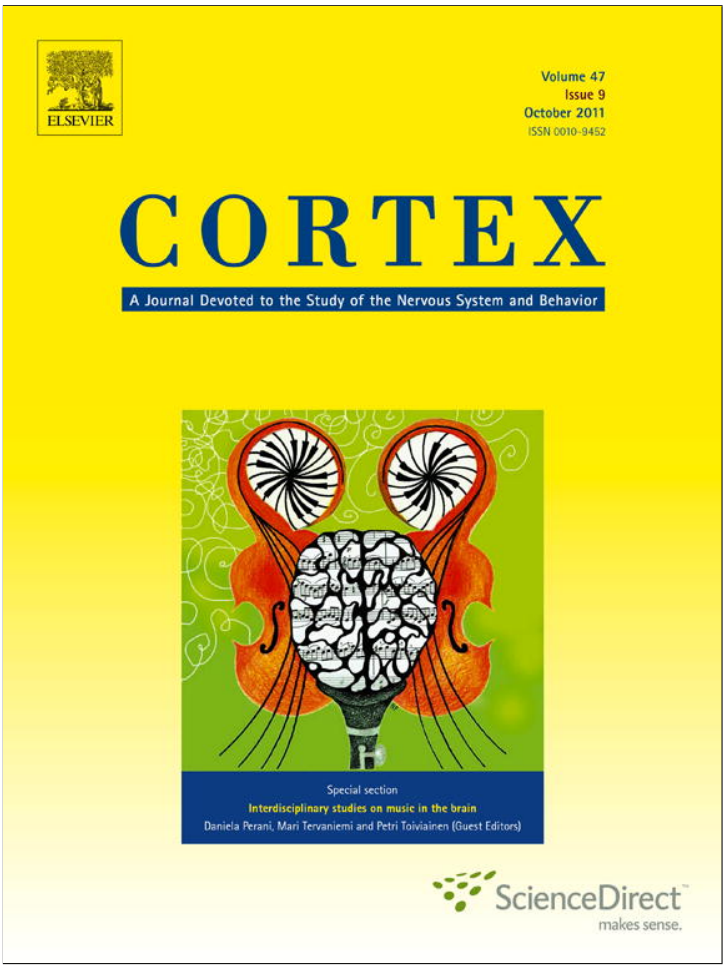

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Research report

When *two* and *too* don't go together: A selective phonological deficit sparing number words

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ABSTRACT

We report the case of an Italian speaker (GBC) with classical Wernicke's aphasia syndrome following a vascular lesion in the left posterior middle temporal region. GBC exhibited a selective phonological deficit in spoken language production (repetition and reading) which affected all word classes irrespective of grammatical class, frequency, and length. GBC's production of number words, in contrast, was error free. The specific pattern of phonological errors on non-number words allows us to attribute the locus of impairment at the level of phonological form retrieval of a correctly selected lexical entry. These data support the claim that number words are represented and processed differently from other word categories in language production.

1. Introduction

Several neuropsychological studies have reported selective impairment or sparing of numerical concepts and number words. At the semantic level, double dissociations between numerical concepts and number words have been documented (Cipollotti and Butterworth, 1995; Cipolotti et al., 1991; Cappelletti et al., 2001, 2002; McCarthy and Warrington, 1990; Dehaene and Cohen, 1997; Thioux et al., 1998; Zamarian et al., 2006). The patient described by Cipolotti et al. (1991), for example, was proficient in semantic tasks involving non-numerical material, but was unable to perform numerical reasoning tasks with numbers above four. In contrast, Cappelletti et al. (2001; see also Cappelletti et al., 2005) reported a case of a patient affected by semantic dementia who exhibited profound semantic deficits across different

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cognitive domains but whose numerical knowledge was intact. Likewise, Zamarian et al. (2006) reported the case of a patient who was markedly impaired in tasks tapping non-numerical semantic knowledge, but whose performance was at ceiling in nearly all numerical tasks. As shown by reaction times, the patient's processing of arithmetical knowledge was fully preserved and indistinguishable from that of healthy subjects.

The existence of double dissociations between number concepts and other concepts has been taken to suggest that dedicated neural circuitries may be involved in storing and processing numerical cognition (Dehaene and Cohen, 1995, 1997; Butterworth et al., 2001; McCarthy and Warrington, 1990, among others). This has been corroborated more recently by neuroimaging studies showing localized activation patterns specific to number processing tasks (see Cantlon et al., 2006; Dehaene and Cohen, 1995; Dehaene et al., 1999, 2003; Cappelletti et al., 2007; Thioux et al., 2002 among others).

In contrast to the large body of studies indicating a semantic dissociation between number and non-number concepts, fewer studies have found dissociations between number and non-number words at the post-semantic word production level, in both spoken and written modalities (Basso and Beschin, 2000; Bachoud-Lévi and Dupoux, 2003; Cohen et al., 1997; Geschwind, 1965; Delazer et al., 2002; Marangolo et al., 2004, 2005; Dotan and Friedmann, 2010). Cohen et al. (1997) and Bachoud-Lévi and Dupoux (2003) reported on patients who, in the spoken modality with picture naming tasks, made phonological errors on all word categories except for number words. The opposite pattern is reported in Marangolo et al. (2005) who described the case of a patient who made errors only on number words, in the spoken but not in the written modality. In the written modality, Basso and Beschin (2000) reported the case of a patient whose written production of Arabic numerals was impaired, but whose spelling and knowledge of the letters of the alphabet was only minimally affected. This contrasts with Delazer et al. (2002), who reported the case of a patient with a written production deficit that affected the letters of the alphabet but not Arabic numerals.

Dissociations between number words and non-number words may indicate that the language system represents and processes number words separately. However, the level of the language production system where the distinction occurs is unclear. We frame our analysis within a broad consensus framework for language production, as developed by Levelt and colleagues (Levelt, 1989; Levelt et al., 1999; see also Bock and Levelt, 1994, and Ferreira and Slevc, 2007, for a recent review). In this model, spoken word production (e.g., producing the word /kæt/ to describe the picture of a cat) involves the retrieval of two different types of lexical representations: *lemmas* specified for syntactic–semantic properties, and modality specific *lexemes* (word forms) specified for morpho-phonological properties (but see Caramazza, 1997, for a model without the lemma/lexeme distinction). In the process of spoken production lexemes are further "unpacked" yielding output phonological representations that then feed into articulatory processes and representations (articulation). The exact nature of these output phonological representations and the amount of phonological and phonetic detail they contain is subject to theoretical debate. For example, some theories (Goldrick and Rapp, 2007) further distinguish between lexical-phonological representations that encode the arbitrary aspects of word forms (e.g., the concept "domestic feline" is arbitrarily associated with the sequence /kæt/ in English and /gatto/ in Italian) and post-lexical phonological representations that encode predictable information ("domestic feline" is phonetically /k^{h}æt/ in English). It is not the goal of the current study to distinguish between these more fine-grained levels at the spoken output phonological level prior to articulation, and in our analyses we will keep the broader divisions of the consensus framework for word production as our reference. Within this broad framework, dissociations between the production of number words and non-number words may occur at distinct post conceptual-semantic levels: the level of *lemma* retrieval, where the syntactic properties of words are specified, or more peripheral output levels of phonological encoding (the lexeme, or the subsequent mapping from the lexeme to lexical and post-lexical representations prior to articulation).

In order to localize a category-specific word production deficit within this functional architecture, an analysis of the type of word production errors is necessary. For example, in order to conclude that a deficit occurs at the level of phonological encoding, one must ascertain that the errors are purely phonological in nature and are not the result of selecting a non-target lemma. This might be difficult to ascertain in the case of aphasic jargon, especially if the errors span over more than one phonological segment or syllable (see Cohen et al., 1997). The number of representational levels and the types of processes also depend on the task. Whereas picture description involves conceptual preparation and lemma selection in addition to lexeme retrieval, repetition and reading tasks may bypass conceptual preparation and lemma selection by recruiting either lexical or sub-lexical acoustic-phonological or graphemic-phonological conversion routes.

In this study, we present data from an individual who exhibits a dissociation in reading aloud between impaired non-number words and spared number words. The patient is similar to the two previously reported ones in the literature (Cohen et al., 1997; Bachoud-Lévi and Dupoux, 2003). There are, however, two crucial differences with the previously reported cases. First the dissociation manifests itself in reading; second, the patient's error pattern in reading is unusually clear and indisputably phonological because it overwhelmingly affects only one segment, namely vowels. A detailed report on the dissociation between vowels and consonants in this patient's production was previously reported in Semenza et al. (2007).

Before reporting the case, we briefly review the two most relevant studies indicating the possibility of production deficits sparing the *lemma* level and involving the phonological level for all word categories except number words.

Cohen et al. (1997) were the first to report in detail a dissociation between non-number words and number words in the production of a Wernicke's aphasic patient and to locate the deficit post-lexically, at the level of phonological form retrieval. With the exception of number words, on which the patient rarely made errors, the patient exhibited neologistic language production and phonological errors across all word categories in all production tasks, including repetition and

reading. His neologistic jargon was characterized by phoneme substitutions (of both consonants and vowels) with preservation of the overall number of syllables of the target in 80% of neologisms. Of these, 54% also preserved syllable structure. The authors did not find differences in error rates for grammatical class, imageability, or an effect of lexical frequency above and beyond length. The exception was number words, on which errors were infrequent, and when present, were mostly lexical (e.g., 250 -> "four-hundred-and-sixty") or syntactic (e.g., 74 -> seven-hundred-and-forty). The patient made very few phonological errors on number words: only six errors out of 470 number word trials were phonological, while 630 errors out of 886 non-number word trials were phonological. On the basis of the observed sparing of number words from errors, Cohen et al. (1997: 1030) concluded that: "(the) category-specific sparing (of number words) suggests that the cerebral lexicon has a categorical organization down to the phonological level".

The evidence that Cohen et al. (1997) used to argue for a phonological locus of the dissociation between number and non-number words, however, was somewhat indirect. The main piece of evidence they used was that errors on non-number word targets often matched the overall phonological structure of the target (i.e., number of syllables and syllable structure). Although the specification of syllabic information pertains to the phonological level of encoding and is thus an indication that the patient's deficit was in retrieving phonological representations, it is not entirely possible to determine whether the patient had selected the appropriate lemma, or whether another lemma with the same number of syllables and syllable structure had been selected.

The second relevant case is reported in Bachoud-Lévi and Dupoux (2003). The patient, GBI, exhibited impaired word production in picture naming tasks sparing numerals, days of the week and months. The patient had very good reading and word repetition.

Unlike the patient in Cohen et al. (1997), this patient's production was affected by grammatical class: abstract nouns and verbs were significantly less affected than concrete nouns. GBI had spared conceptual knowledge and could correctly assign gender to 95% of the items he could not name, indicating intact lexical access to lemma information. In order to localize GBI's deficit, the authors examined the naming error patterns. In 70% of the productions, GBI preserved the syllable length of the target. More importantly, the errors were overwhelmingly phonological in nature, consisting of phonemic paraphasias and non-words that often resembled the target in metrical properties (e.g., number of syllables). These phonological errors constituted 86% of the errors, and of these, 78% preserved the number of syllables of the target.

Another indirect piece of evidence suggesting that GBI's deficit concerned word form retrieval is that variables such as frequency and length affected naming accuracy. These variables have been argued to influence phonological encoding (Jescheniak and Levelt, 1994; but see Dell, 1990 and Navarrete et al., 2006 for evidence that frequency may operate at other levels, including lexical retrieval, and Goldrick and Rapp, 2007 for evidence that lexical frequency operates on what they call lexical-phonological representations, but not post-lexical ones). We will return to the issue of frequency in the General discussion.

In the case we report here, two aspects of the data strongly suggest that the localization of the dissociation is at the level of phonological form encoding: first, given that the task was a reading one, the target word was always known, making lexical miss-selection less likely; second, the errors on non-number words were errors on individual segments, while the rest of the segmental content of the target word was intact. For example, for the target word *feroci* (/ferotʃi/ "fierce", masculine plural, CV.CV.CV structure) the patient produced the non-word **ferici*, substituting the fourth segment, i.e., the vowel /o/ with the vowel /i/. The fact that both the syllabic structure and most of the segmental content of the target word are preserved (CV.CV.CV and /f/ /e/ /r/ /tʃ/ /i/), provides very strong evidence that the patient has retrieved the lemma and much of the phonological content of the corresponding lexeme. In sum, the data from this patient may allow a more precise functional localization than previously reported cases and support the proposal that number words are produced differently from other words, down to the phonological level of lexeme retrieval of a selected lemma, or potentially even more "downstream", in the mapping from the lexeme to the subsequent level of phonological assembly, prior to articulation. In models that distinguish between lexical-phonological and post-lexical phonological representations, such as Goldrick and Rapp (2007), this could even be at the post-lexical-phonological level. We discuss this latter possibility in the General discussion.

2. Case history

GBC was a 62-year-old businessman, with a long history of vascular problems. In February 1998, he suffered from an ischemic lesion in the left posterior temporal area, resulting in fluent aphasia. An old ischemic lesion in the left occipital lobe was also found on that occasion. In May 1998, he underwent a bypass between the superficial temporal artery and the middle cerebral artery. The procedure was complicated a few days after the intervention by bleeding in the left temporo-parietal area. An magnetic resonance imaging (MRI) taken in April 2005 revealed a vascular lesion in the left posterior middle temporal region.

In December 2004, GBC was first seen at the Neurology Department of the Istituto Auxologico Italiano, in Verbania, Italy. Since then he was followed in the Auxologico outpatient clinic. GBC was tested between January 2005 and May 2005 (reported in Semenza et al., 2007; see also Romani et al., 1996, 2002) and subsequently between September 2007 and September 2008. GBC provided his informed consent and collaborated rather enthusiastically in all phases of the study, which was conducted according to the procedures of the Istituto Auxologico.

2.1. *Assessment of language functions*

GBC's full neuropsychological evaluation revealed significant symptoms for aphasia only. GBC's language functions were evaluated with a battery of tests, including the Italian version

of the Aachener Aphasia Test (Luzzatti et al., 1996), and portions of the Batteria per l'Analisi dei Deficit Afasici (Battery for the Analysis of Aphasic Deficits) (BADA) (Miceli et al., 1994). GBC's aphasia was stable during the investigation and was distinguished by well-articulated, relatively fluent, paraphasic and paragrammatic speech, severely affected repetition and naming, and moderately impaired auditory comprehension. During examination, a striking pattern of phonological errors emerged: GBC appeared to make errors on vowels but not on consonants. We have reported in detail on the consonant–vowel dissociation in another study (Semenza et al., 2007); here we focus on his performance on number words and on non-number words. GBC's selective and unusual phonological deficit on non-number words allowed us to localize the deficit functionally as a deficit in word form encoding for non-number words, which contrasts with his preserved word form encoding for number words. Data from the neuropsychological assessment are reported fully in Semenza et al. (2007) and are summarized in Table 1.

2.2. *Reading connected prose aloud*

A detailed examination of the error corpus is reported elsewhere (Semenza et al., 2007). Here we summarize the relevant findings that allowed us to conclude that GBC's errors on non-number words were at the level of phonological form encoding.

GBC read an article consisting of 2882 words. We examined only those errors that could be conservatively attributed to phonological factors. This yielded an error corpus of 111 non-words (*) where one (in most cases) or more phonemes were substituted in response to given target words (*islimica** instead of *islamica*, "Islamic"; *ferici** instead of *feroci*, "ferocious"; *sembre** instead of *sembra*, "it seems"). The corpus contained a total of 407 vowels. There were 113 vowel substitution errors. A few facts about the Italian vowel system are important to bear in mind. Unlike English, Italian has a system of cardinal vowels that do not undergo reduction processes in weak syllables, so it was always possible to correctly identify the quality of the vowel produced; this was judged to be a fully articulated Italian vowel by independent coders with 100% agreement (see Semenza et al., 2007). Errors occurred in all word categories, irrespective of frequency or grammatical class. Errors were selectively on vowels, with a 7:1 ratio over consonants. Vowels were substituted with other vowels from the Italian vowel inventory. This finding is in contrast to GBC's performance on number words, which we address in the following section.

GBC's error-free production of number words suggests that the phonological encoding process for number and non-number word production is qualitatively different. As we discuss later (see Section 3 below), number words are produced by GBC with no segmental errors on vowels or consonants. The contrast between the selective phonological deficit at the level of vowel selection for non-words and the preserved production of number words suggests separate representations/processes in the production of words versus number words. We return to this in the General discussion.

Table 1 – GBC's number of errors on language tasks (Aachener Aphasia Test, Italian Version, Luzzatti et al., 1996; BADA, Miceli et al., 1994).

		Task	Number of errors
Phonemic tasks	Auditory discrimination	Phonemic discrimination	7/60
		Phoneme to grapheme matching	6/60
Lexical tasks	Lexical decision	Auditory real word	13/40
		Auditory non-word	1/40
		Written real word	2/40
		Written non-word	4/40
	Lexical discrimination: same word or not?	Written (different fonts)	0/40
Word production tasks	Object and action naming		40/58
	Repetition		32/45
	Single word reading		10/92

2.3. *Number words: repetition and reading tasks*

GBC had a digit span of four. In a number repetition task, he correctly repeated complex numbers 1–3 digits long (30/30). GBC read aloud complex numbers (in both Arabic and alphabetic codes) up to eight digits (50/50) without committing phonemic errors. He made four lexical substitutions (e.g., "sixty one" instead of "fifty one"); and no syntactic substitutions. The category of numbers was thus found to be an exception within his phonological problem. This observation motivated further investigation.

3. Experimental investigation

This investigation was conducted from September 2007 to September 2008. Relative to the first testing period (Semenza et al., 2007) the patient's symptoms had much improved.

In the experimental reading aloud tasks reported below, he did not make lexical errors.

We report GBC's reading performance on non-number words belonging to different grammatical categories and varying in frequency and length. We examine the effects of grammatical class, frequency and length on GBC's errors to ascertain whether indeed number words are selectively spared in this patient and whether this is due to number word status and not correlated properties such as the fact that basic-number words are frequent and short. While the presence or absence of a frequency effect may be an indication of the functional location of the deficit, we wish to emphasize that we are not relying on the frequency analysis to locate the deficit, given the controversies in the literature as to the locus of frequency effects. As discussed in the Introduction, the nature of the task (reading) and the nature of the errors made by GBC on non-number words (segmental errors on vowels) allow for a functional localization based on more direct evidence. We report GBC's performance on number words and

words which were chosen to be on average shorter and more frequent than what we call basic-number words, that is, words for digits (one–ten), teens (eleven–nineteen), tens, hundred, thousand, million, billion.

Some facts about basic-number words in Italian need to be considered. Basic-number words in Italian are one to four syllables in length and vary in stress pattern (*tré*, three; *quàttro* four; *ùndici*, eleven). Complex numbers (e.g., 4562) in alphabetic code are written as single words in Italian (e.g., *quattromilacinquecentosessantadue*, fourthousandfivehundred-sixtytwo). Little is known about complex number repetition and reading, but it is possible that complex numbers are parsed into smaller sequences of basic-numbers (e.g., four, thousand, five, hundred, etc.).

3.1. Non-number word reading

We examined GBC's reading of words belonging to different grammatical classes, and varying in length and frequency. GBC was presented with 125 non-number words. All of the words were taken from BADA (Miceli et al., 1994). There were 20 adjectives, 35 function words, 35 nouns, and 35 verbs. Two lists were created by randomizing all of the items and presented on two testing session, approximately 1 week apart. A summary of stimulus characteristics, their frequency and length, is shown in Table 2.

3.1.1. Results

GBC made 23/125 (18.4%) phonemic errors (Table 3). To determine whether the probability of producing an error was affected by grammatical category, we ran a binomial logistic regression, predicting error (error, correct) as a function of frequency, length, and grammatical class. Frequencies for each word were obtained from the Corpus e Lessico di Frequenza dell'Italiano Scritto (Corpus and Frequency Lexicon of Written Italian) (COLFIS) Corpus, a written corpus of Italian, consisting of 3,798.275 words (Bertinetto et al., 2005). Frequencies were log transformed. We used a forward stepwise regression analysis in which predictors are entered into the model only if they make a significant improvement to the fit of the model relative to a model without that predictor. Log Frequency was neither a significant predictor ($p = .2$), nor was length in number of characters ($p = .19$), nor length in number of syllables ($p = .54$). Grammatical category was also not a significant predictor ($p = .21$).

In summary, neither frequency, nor length, nor grammatical category, were significant predictors of GBC's errors in reading non-number words.

Table 3 – GBC phonological errors by grammatical category.

Category	Errors
	Count mean
Adjectives	7/20–35%
Nouns	5/35–14.3%
Verbs	5/35–14.3%
Function	6/35–17.1%

3.2. Number word reading

GBC was asked to read aloud 54 numbers (2–8 digits long) written in Arabic code, (e.g., "52") and 23 number words (2–6 digits long) written in the alphabetic code (e.g., *cinquantadue*, "fifty-two"). None of the words consisted of a single basic-number word.

3.2.1. Results

GBC correctly read all number words, in Arabic code and alphabetic code (77/77 correct).

3.3. Discussion

In reading non-number words, no effect of frequency, length or grammatical class emerged. However, the non-number word lists reported in Section 3.1 (lists of words from BADA) contained words that are on average less frequent and longer that basic-number words. To ascertain that the sparing of number words from phonemic errors is a consequence of their number word status, and not due to the high frequency of basic-number words into which a complex number can be parsed, an additional list was constructed. This additional list consisted of words that were, on average, more frequent than basic-number words (t (1, 30) = 2.9, $p = .007$, corrected for unequal variances) and shorter than basic-number words (t (1, 39) = 2.1, $p = .04$, corrected for unequal variances).

3.4. Additional testing: reading high frequency and short non-number words

3.4.1. Materials and procedure

GBC read a list of 302 words. The list contained prepositions, articles and conjunctions, presented in random order. There were 46 different types of prepositions (12 simple and 34 complex prepositions, consisting of the preposition plus the definite determiner, e.g., *al*, "to" + "the", or *del*, "of" + "the").

Table 2 – Non-number words: frequency and length by grammatical category.

Category	Log Freq			Syllables			Characters		
	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
Adjectives ($n = 20$)	3.3	1.2	1.4–5.4	3.1	.55	2–4	7.3	1	6–9
Nouns ($n = 35$)	3.8	1.2	1.6–6	3	.61	2–4	7.5	1	6–10
Verbs ($n = 35$)	2.8	1.5	0–5	3.2	.47	2–4	7.6	1	6–10
Function ($n = 35$)	4.7	1	2.8–7.3	3	.34	2–4	7.5	1.1	6–11

Each preposition was repeated 3–4 times for a total of 145 preposition tokens. There were 11 different types of articles (seven definite and four indefinite), repeated 10–11 times each, for a total of 118 article tokens. There were 23 conjunction types, repeated 1–2 times each for a total of 39 conjunction tokens.

3.4.2. Results

3.4.2.1. PHONEMIC ERRORS. Errors resulting in another real word (e.g., *la* instead of *le*, or *a* instead of *e*) were conservatively excluded from the error count. GBC made 16 phonemic errors (13 on vowels and three on consonants). Eight errors occurred on prepositions: three on simple prepositions (*su*, *fra*, *in*) and five errors on complex prepositions (*agli*, *alla*, *della*, *dei*, *sugli*). Five errors occurred on articles, three on indefinites (*un*, *uno*, *una*), and two on definites (*lo*, *gli*). Three errors occurred on conjunctions (*neanche*, *tranne*, *che*).

3.4.2.2. COMPARISON OF HIGH FREQUENCY SHORT NON-NUMBER WORDS WITH NUMBER WORDS. The materials for the high frequency, short non-number word list were chosen to be more frequent and shorter than basic-number words. We thus compared GB's errors on number words versus non non-number words. GBC made significantly more errors on non-number words that on number words (16/302 *vs* 0/77, $\chi^2(1) = 4.3$, $p = .04$).

3.4.2.3.
To determine whether the lack of effects of grammatical class, length, and frequency reported above was simply due to the paucity of stimuli used in the previous set of words, we ran a logistic regression analysis combining all the words that were presented to GBC (the original set of 125 from BADA, the 302 frequent short words and the 73 number words). We ran a binomial logistic regression, predicting error (error, correct) as a function of frequency, length (in number of characters and number of syllables), grammatical class, and number word status (number *vs* non-number word). Log Frequency was neither a significant predictor ($p = .76$), nor was length in number of characters ($p = .6$), nor length in number of syllables ($p = .7$). Grammatical category was also not a significant predictor ($p = .11$). Number word status was the only significant predictor ($p = .007$).

3.5. *Reading number words embedded in non-number words*

Although basic-number words do not differ phonotactically from non-number words in Italian, we examined whether it might be the particular sequence of phonemes in number words that is encoded and preserved in GBC. To test this hypothesis, we created stimuli in which a longer word (e.g., *alisei*, "trade winds") contained a sequence embedding a number word (*sei*, "six"). GBC was asked to read aloud 75 words that contained a homophonic sequence. GBC made 16 vowel substitutions, four of which occurred on the sequences homophonic to number words.

A second task was devised, in which the homophonic sequences used in the previous task (*otto*, *sei*) were embedded in 75 non-words, which were derived from the previous corpus by changing one or two phonemes from the non-number part of the words. GBC made 20 vowel substitutions, four of which were on the sequences homophonic to number words (e.g., **alizai* instead of *alizei*). Number words were not spared when contained in words or non-words.

3.5.1. *Producing number words in naming tasks*

Given that a preliminary analysis revealed that GBC's phonological errors on non-number words appeared both in spontaneous speech as well as in more constrained tasks (e.g., picture naming) in addition to reading and repetition tasks, GBC's production of number words was explored through a series of additional oral naming tasks.

3.5.1.1. NAMING THE RESULT OF ARITHMETIC OPERATIONS. This task consisted in naming the result of simple arithmetic operations. GBC was given 80 additions ($30 + 15$) and 80 subtractions ($21 - 4$) in written format. Half of the problems were written in Arabic code and half in alphabetic code. GBC was asked to read aloud the operation ("thirty plus fifteen") and then to provide the result orally ("equals forty-five"). GBC made arithmetic errors (60/160), mostly due to his confounding of arithmetical signs (e.g., $21 - 4 = 25$) or perseveration of an earlier result, however he never produced a phonemic error in either reading or orally producing the result.

3.5.1.2. NAMING GENERAL AND PERSONAL NUMERICAL FACTS. GBC was given 20 questions about general and personal facts requiring a numerical response (e.g., *How many days are there in a year? At what age did you finish school? What is your shoe size?*). Again, GBC never made phonological errors. Due to his auditory problems, questions had to be repeated approximately 50% of the time. Once GBC understood the question, his response was error-free.

GBC's production of number words was shown to be phonologically correct across a series of tasks requiring spoken output. The sparing of number words cannot be imputed to their frequency, length or abstractness.

4. General discussion

GBC's performance in reading aloud number and non-number words is striking in two respects. On non-number words, GBC made more phonological selection errors on vowels than on consonants. On number words, in contrast, GBC made no phonological errors.

Semenza et al. (2007) proposed that GBC's deficit supports a "slot and filler" architecture of word production (e.g., Dell, 1988; Levelt, 1992) for non-number words in which lexemes are further broken down into separable representations: structural information consisting of consonant–vowel status and content information consisting of segmental information. This model finds support from the study of spontaneous and elicited speech errors (Meyer, 1992; Shattuck-Hufnagel, 1979; Treiman, 1983; Dell, 1988), aphasia (Blumstein, 2001), and in priming experiments in normal word production (Sevald et al., 1995).

Figs. 1 and 2 illustrate the proposed representations and processes involved in the spoken production from written input of non-number (Fig. 1) and number words (Fig. 2) and the

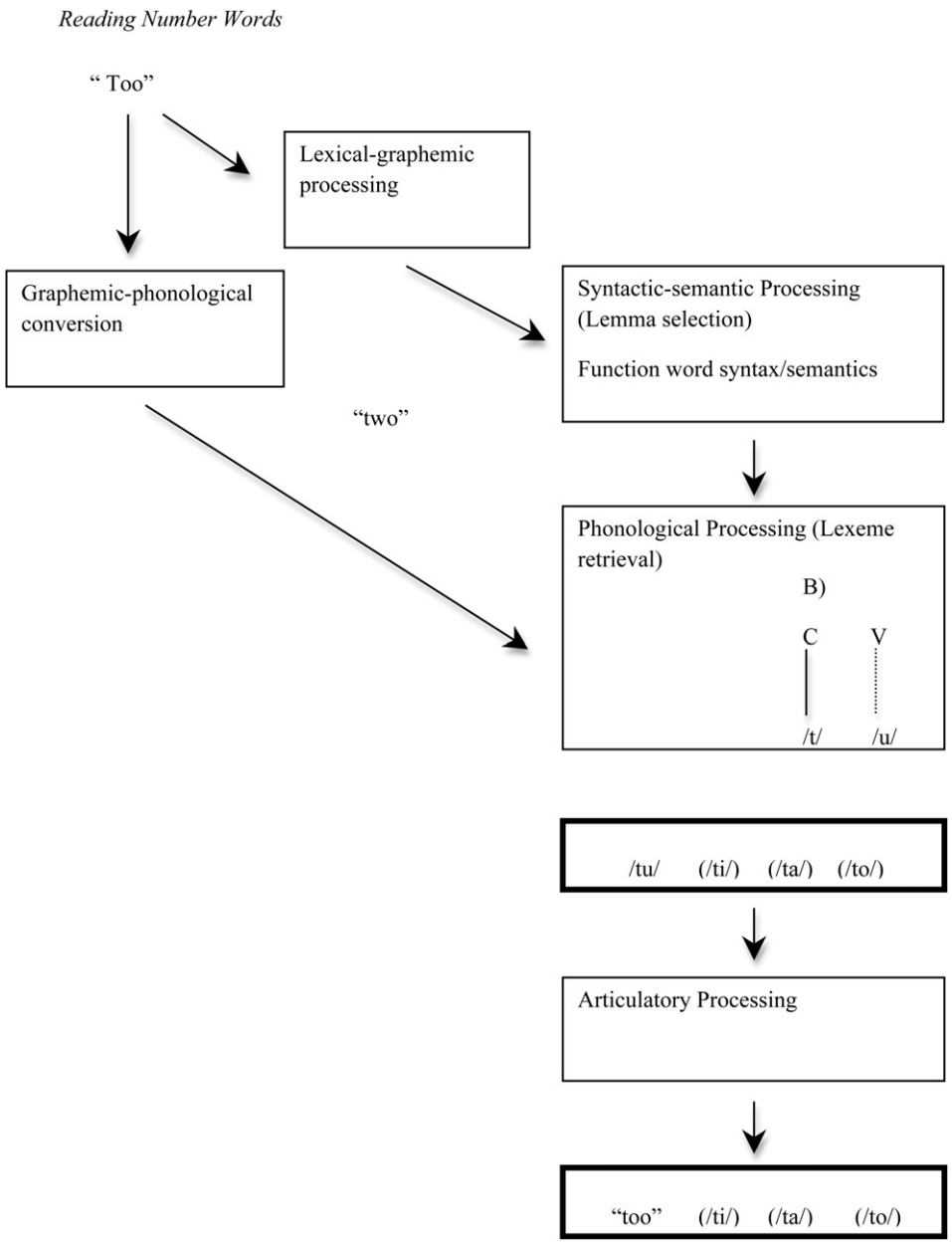

Fig. 1 – Phonological encoding in reading non-number words: The lexeme includes an abstract tier for consonant and vowel slots with impaired linking (dotted lines) between the abstract tier and the vocalic slots. Impaired production may result in non-word with different vowel, e.g., /ti/, /ta/, /to/.

proposed locus of impairment for GBC's selective production deficit. We assume a standard dual-route architecture (Coltheart et al., 2001) in which single word reading can be achieved through a lexical route (via access to the lemma and associated semantic-syntactic properties) as well as through a sub-lexical route that coverts orthographic representations into phonological ones. Crucially, within the phonological processing level, a modality specific lexeme is retrieved which contains a separable representation of timing slots specified for consonant/vowel slots, or CV tier (Fig. 1), in addition to segmental slots (phonemes). The link between the abstract V slot and its segmental content is selectively impaired in GBC. The impaired mechanism that links the segmental content to its slot is unknown, but it is possible that a phonological buffering process is involved (e.g., Caramazza et al., 2000; Dotan and Friedmann, 2010) which maintains representations active while other operations are performed. Crucially, based on the neuropsychological evidence for consonant–vowel dissociations, the buffer has to include a mechanism that is sensitive to the phonological nature of the representations it keeps active (their consonant–vowel status).

GBC's error-free production in reading number words, in contrast, suggests that the phonological representations/processes for number words are qualitatively different from that of non-number words and is compatible with two representations: (1) an intact abstract CV level and intact links

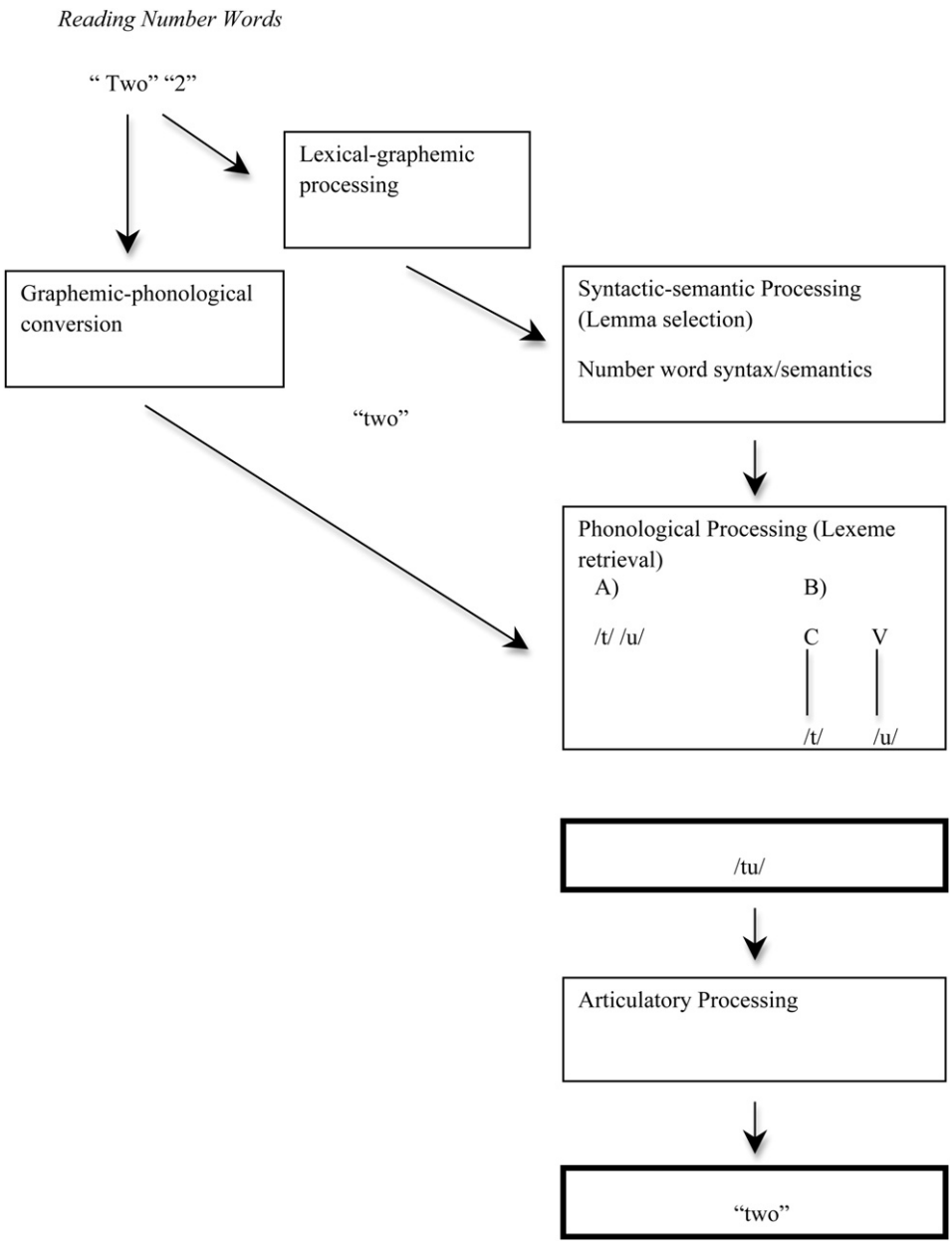

Fig. 2 – Phonological encoding in reading number words: The lexeme either directly specifies filled out segmental content: (A); or includes an abstract tier for consonant and vowel slots with preserved links (solid lines) between the abstract tier and the segmental content: (B).

from the consonant slot and the vowel slot to their respective consonant and vowel segmental fillers (Fig. 2 version A) and (2) a direct link between graphemic input and surface phonetic form such that the phonetic forms of number words are retrieved with segmental information already spelled out, without the abstract CV tier (Fig. 2 version B). GBC's data show that number and non-number word production dissociate all the way down to the phonological level, but alone cannot distinguish between the two alternative representational steps for number words. If the first alternative is correct and number words also require an abstract CV level and a segmental level, one should be able to find patients who show the same selective dissociation between consonant and vowels on number words, but not on non-number words. To our knowledge, no such case has ever been reported. The second alternative makes the (strong) prediction that patients with phonological deficits at the word activation level should be relatively less impaired when producing number words than other word categories. The pattern of errors on number words should also be qualitatively different: whereas non-number words are vulnerable to segmental errors, number words should not be. Errors on number words should target the entire lexical unit, but not its individual segments. This prediction seems to be borne out in the studies that report errors on number words (Cohen et al., 1997; Bachoud-Lévi and Dupoux, 2003; Marangolo et al., 2004, 2005; Caño, et al., 2008):

errors on number words are either lexical substitution errors (e.g., 250 -> "four-hundred-and-sixty") or syntactic errors (74 -> seven-hundred-and-forty). Messina et al. (2009) analyzed the performance of an unselected group of left-brain-damaged aphasic subjects in order to explore the effect of stimulus type on the production of words and number words (see also Dotan and Friedmann, 2010 for a brief report of similar data). They showed that phonological paraphasias were the most frequent error in the production of words, whereas lexical substitutions were the most frequent error with number words. Almost no phonological errors occurred on number words.

If we include a buffering mechanism (Dotan and Friedmann, 2010) along the lines of what has been assumed for spoken production of non-number words, the following account seems plausible: the buffering mechanism in the case of number words operates not over segmental units (consonants and vowels) but over basic-number words. This would provide one mechanism to account for the qualitatively different errors made on non-number words versus numbers. Errors on number words have come to be known as lexical/syntactic substitutions, but we can consider these as "phonological" if we assume different phonological units operating as memory "chunks" for number and non-number words.

We have functionally located GBC's impairment broadly at the level of phonological encoding (lexeme retrieval), because whereas there is general consensus with regards to the overall architecture for production, different models either further break down the functional distinctions at each level (e.g., within the lexeme) or assume additional levels between the lexeme and articulatory planning. Based on the different patterns of performance on repetition and naming of two aphasic patients, Goldrick and Rapp (2007) argue for two post-lexeme phonological levels of representation called the lexical-phonological and the post-lexical phonological level. The lexical-phonological level is a relatively abstract level of representation encoding segmental information but not featural information, which is specified in the post-lexical phonological level of representation. Variables such as word frequency are assumed to operate at the lexical but not the post-lexical level of representation. Goldrick and Rapp (2007) also make the suggestion that the phonological buffer may operate post-lexically (but also allow for the possibility of a role upstream). Given the fact that GBC's articulation is intact, his deficit can be located somewhere between the lexeme (either in its representation or access) and more peripheral phonological representations. The exact locus of his deficit will in part depend on the number of levels assumed by different models. Speculatively, the absence of a frequency effect on GBC's performance may be an indication that the deficit is at the post-lexical phonological level, and may reside in the buffering mechanism. Note however that the post-lexical buffer would have to be sensitive to the different phonological representations units (vowels *vs* consonants in the case of non-number words, and multi-segment basic-number words in the case of number words).

The ultimate reason for the dissociation, in production, between number words and other word classes is still poorly understood. In addition to belonging to the domain of numerical cognition, which is distinct from other domains, number words also have special lexical and syntactic properties that distinguish them from other words. Unlike other word classes, numbers are recursive and consist of basic lexical units (single digits, teens, the units for hundred, thousand, etc.), which combine following syntactic rules that specify the order of units in the case of complex numbers. In the case of GBC, as was the case for the patient described in Cohen et al. (1997), there is no reason to attribute the dissociation to the conceptual level, rather than to the particular lexical properties of number words. Our study, in addition, rules out frequency, length and phonotactics as factors: while it is possible to imagine that high frequency words such as articles (e.g., "the") could be retrieved as pre-assembled phonological units (i.e., [ðə] instead of CV), thus being responsible for the lack of segmental errors, GBC's performance shows that this is not the case. GBC made phonological errors on high frequency function words and the only word category spared from phonological errors was that of number words (but see Dotan and Friedmann, 2010 for recent evidence that other linguistic units such as prefixes and frequent morphemes may also be retrieved as units).

GBC's deficit could be an access or a storage problem, and our data cannot be used to distinguish between the two possibilities. Apart from the cases in Cohen's et al. (2007) and Bachoud-Lévi and Dupoux, (2003), the closest analog in the literature for the reading task is perhaps the patient IH, who was perfect on reading (and writing) number words, but very impaired on non-number words (Butterworth et al., 2001). In this patient, both written and phonological forms were intact, as evidenced by lexical decision tasks, but access to non-number words in both writing and reading was severely affected. However, in the case of IH, reading errors on non-number words were not purely phonological. IH's impairment was in access via semantics (Cappelletti et al., 2002). Differently from IH, GBC was fairly good at lexical decision tasks on written words, and could reliably reject auditorily presented non-words, (but was less proficient at accepting real words). This may make GBC different from IH and leaves open the possibility of an access deficit, rather than a radical difference in the storage of number words.

In addition to adding new data and novel proposals for the mental representation of number words, this study suggests a revision of current models of language production that takes into account morpho-phonological differences between different word classes. The data from GBC add two important findings to models of language production: (1) evidence for an abstract CV tier and selectively disruptable links between the abstract tier and the segmental tier for non-number words (Semenza et al., 2007); (2) evidence that, differently from non-number words, number words may maintain intact links between the CV tier and the segmental tier; or, more radically, it might be taken to suggest that number words do not require the additional CV tier. Either way, number words have been shown to dissociate from non-number words at the relatively "late" level of phonological encoding in production, prior to articulation.

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