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Selective impairment for reading numbers and number words: a single case study

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Abstract

The article reports the case of a patient who showed a selective inability in reading multi-digit numbers following recovery from aphasic disorders. Although his ability to read words, non-words, syntagms and sentences was almost preserved, he made errors with Arabic numerals and number words. Different types of errors with alphabetic material were also observed: he made only rare phonological substitutions with linguistic stimuli, whereas errors were almost always lexical in reading number words. A series of experiments showed that his ability to access number semantics was intact. In contrast, he selectively failed in all production tasks (including calculation), but only when the required response was in the oral output modality. This pattern was interpreted in terms of a selective deficit to the spoken number name production system. Furthermore, the different types of errors made with alphabetic materials belonging to the two classes of stimuli (numerical versus non-numerical) further support the hypothesis of a categorical organisation in the lexical-semantic system.

Keywords: Number processing; Number words; Transcoding tasks; Sublexical mechanisms

1. Introduction

The dissociation between preserved ability in processing Arabic numerals and selective impairment in reading alphabetic material has been widely described (Albert, Yamadori, Gardner, & Howes, 1973; Anderson, Damasio, & Damasio, 1990; Hécaen & Kremin, 1976). In contrast, there are few reports of the opposite pattern, that is, a specific deficit in processing Arabic numerals relative to alphabetic stimuli (letters and words) (Cipolotti, 1995; Cipolotti, Warrington, & Butterworth, 1995; for a review see Delazer & Bartha, 2001).

In most cases, the observed dissociations imply that independent mechanisms subserve the processing of alphabetic and Arabic codes and suggest that there is a similar pattern of performance for words and number words, since both consist of alphabetic elements. Cipolotti et al. (1995) reported the case of a patient who could read aloud letters, words and number names from 1 to 10, although he was unable to read the corresponding Arabic numerals. The same dissociation was described in another case that showed a selective impairment in reading multi-digit numbers aloud with preserved ability to read alphabetic materials (letters, words and number names) (Cipolotti, 1995). In a follow up single case study, after 4 years of language rehabilitation, Delazer and Girelli (1997) documented a differential pattern of improvement for alphabetic and Arabic materials with better performance in reading words and number words than in reading Arabic numerals.

In recent years, several models of number transcoding have been proposed to account for the observed dissociation between Arabic numerals and number words. In McCloskey's model (for a review see McCloskey, 1992) (Fig. 1), functionally independent script-specific modules for the comprehension of Arabic numerals and number words translate the numerical input into an abstract semantic representation. This representation activates an independent output lexicon for the spoken production of numerals and for the written production of Arabic numerals and number words. Thus, the model implies that there are independent mechanisms for the comprehension and production of numbers in Arabic and verbal (alphabetic) codes and suggests that a single semantic route is activated in reading aloud Arabic numerals and number words. In contrast, Dehaene's

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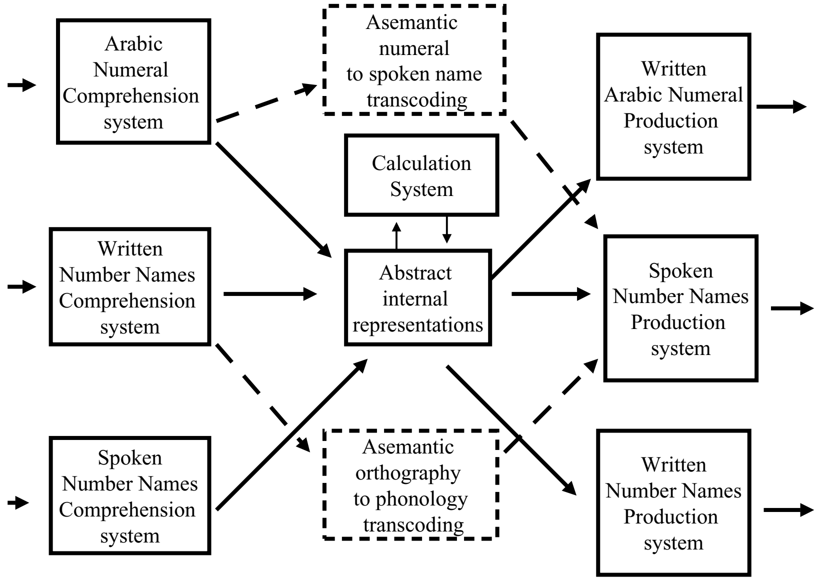

Fig. 1. McCloskey's (1992) model of number processing. Dashed arrows and boxes represent additional asemantic routes for reading Arabic numerals and number words postulated by Cipolotti and Butterworth (1995).

triple code model (Dehaene, 1992; Dehaene & Cohen, 1995) postulates the existence of a direct route linking the Arabic and verbal codes. Therefore, the model assumes that subjects can read Arabic and verbal numerals without having to process information through a semantic representation of quantities (see Fig. 2). However, both models (Dehaene, 1992; McCloskey, 1992) do not make predictions about the relationship between the mechanisms involved in word and number word reading.

In the case of a semantic deficit in the number or in the language categorical domain, the presence of a dissociation between words and numbers is well documented (Cipolotti, Butterworth, & Denes, 1991; Butterworth, Cappelletti, & Kopelman, 2001; Thioux et al., 1998). However, it is not clear at all whether this distinction also holds at a more peripheral level of the speech production system. Although in most cases a similar pattern of performance has been observed for both types of stimuli, contrasting results have also been reported. Noel and Seron (1993) described a patient who was able to read words but had difficulties in reading Arabic numerals and number words. However, the authors only investigated the patient's errors in Arabic numeral reading, demonstrating that they were due to a deficit of the Arabic comprehension system. Similarly, Cipolotti and Butterworth (1995) reported the case of a patient who could not read multi-digit Arabic numerals and written number names aloud despite his good performance in word and non-word reading. Since their patient had no difficulty in comprehending and producing numbers, the authors proposed a modified version of McCloskey's model by incorporating additional asemantic processing pathways. In particular, they suggested that their patient's inability

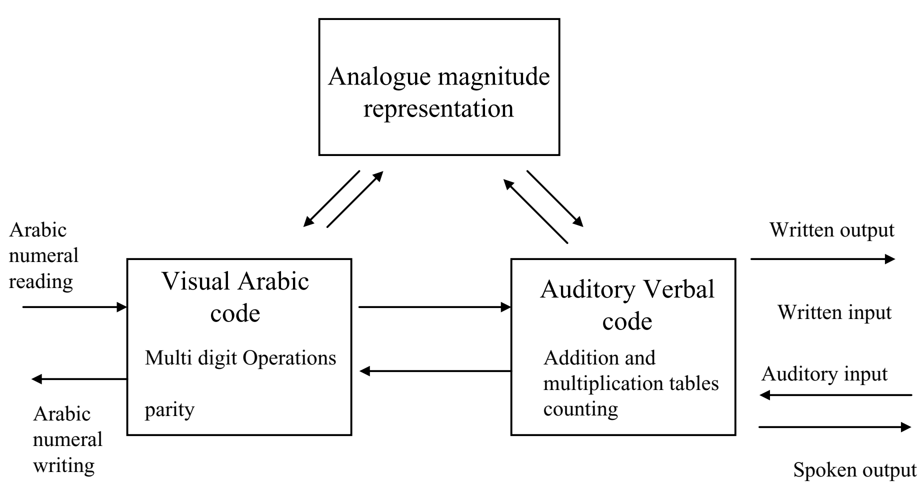

Fig. 2. Dehaene's (1992) triple code model of number processing.

to read Arabic numerals aloud was due to a deficit in the Arabic numerals to spoken number name conversion rules. Furthermore, his impairment in reading written number names aloud was due to a deficit in the mechanisms directly translating orthography into phonology (see dashed part of Fig. 1).

Cohen, Verstichel and Dehaene (1997) presented a patient suffering from severe neologistic jargon affecting word and non-word reading as well as picture naming. In contrast to his severe speech impairment, the patient made no phonological, but only lexical, errors when reading Arabic numerals and written number words aloud. To explain the dissociation between different types of errors in word and number word reading, the authors provided three different interpretations. First, they suggested that words and number words belonging to different semantic domains could be categorically organised also at the level of phoneme selection. Thus, the lexemes of a given category of words, such as numbers, could be selectively impaired or spared, leading to category-specific lexical errors. Second, they hypothesised that number words are spared of phonological errors because they are over-learned word series, produced as automatic speech. Therefore, they might benefit from particular access mechanisms different from those activated during propositional speech. A third interpretation relates to the fact that number words can be combined to form complex words behaving as entire phonological entities. Damage at the level of these units would result in the substitution of another entire number word, while in the case of other types of words, substitution would affect individual phonemes.

Recently, Basso and Beschin (2000) described the case of a patient who made many misspellings in writing number names but only a few in writing words. Following the suggestion by Cohen et al. (1997), the authors explained the dissociation by hypothesising the presence of selective damage to the number category at the level of orthographic production.

Here we present the case of a patient who showed a selective deficit in number processing following recovery from aphasic disorders. Although he was almost unimpaired in reading aloud letters, words, non-words and sentences, he made errors in reading aloud four- and five-digit Arabic numerals and number words. A series of experiments was carried out to determine whether the patient's number reading impairment was due to a deficit in the comprehension and/or production systems.

2. Case report

F.A., a 60-year-old male accountant, with 13 years of education, was referred to our institute in April 2001 for language rehabilitation. In December 2000, he suffered a cerebral ischemia that left him with aphasia. A neurological examination showed no sign of hemiparesis, visual hemifield deficit or hemisensory loss. An MRI scan (August 2001) showed a left temporo-parietal infarct (see Fig. 3). Language was examined using the BADA (battery for the analysis of aphasic disorders, Miceli, Laudanna, Burani, & Capasso, 1994), which evaluates phonological, lexical-semantic and syntactic abilities. His speech output was fluent with moderate anomia. Phonological errors were present both in word and non-word repetition and reading aloud. These difficulties also affected the oral naming task, although less severely. He made orthographic errors in word and non-word writing to dictation. His oral comprehension was well preserved for words and impaired for sentences. The patient underwent 6 months of language rehabilitation.

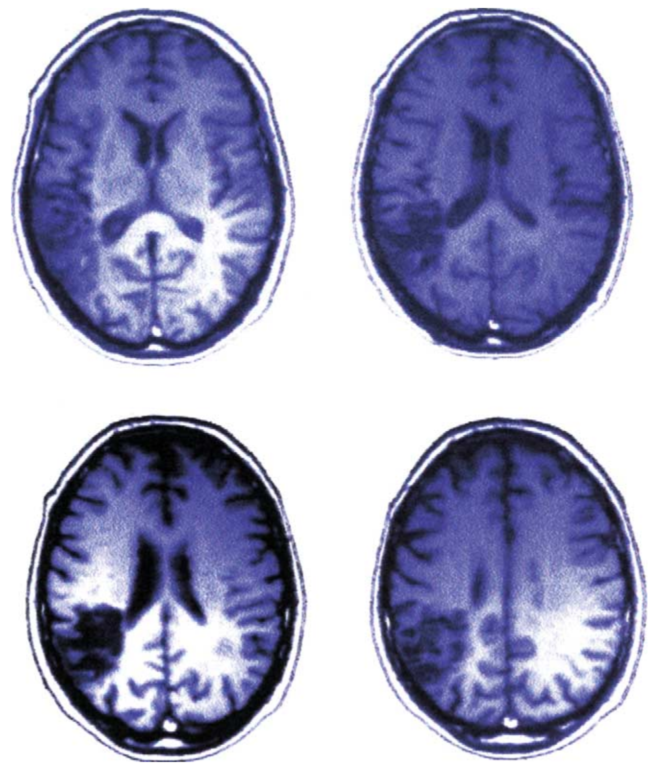

Fig. 3. MR image showing F.A.'s left temporo-parietal infarct.

2.1. Neuropsychological investigation

At the time of the experimental investigation (October 2001), F.A. underwent a series of neuropsychological tests. He performed normally on Raven's coloured progressive matrices (score: 30/36, cut-off 18, Basso, Capitani, & Laiacona, 1987) and he showed no oral, ideomotor, ideational or constructive apraxia. His performance on word and digit memory span was low (score of 3 on both tasks, Orsini et al., 1987; Spinnler & Tognoni, 1987). At the second examination, his language deficit was almost totally recovered. His automatic speech was very well preserved (reciting the days of the week and the months of the year, reciting prayers, counting forward from 1 to 20). He correctly read aloud words, non-words up to three syllables and

Table 1
F.A.'s number of errors on the language examination tasks (BADA, Miceli et al., 1994)

		Task	Number of errors
Phonemic tasks		Auditory discrimination	3/60
	Non-word	Repetition	8/36
		Reading	2/45
		Writing	6/25
Lexical tasks	Lexical decision	Auditory	3/80
		Written	1/80
	Transcoding tasks	Repetition	5/45
		Reading	0/92
		Writing	3/46
	Auditory comprehension	Nouns	0/40
		Actions	0/20
	Written comprehension	Nouns	0/40
		Actions	0/20
	Noun naming	Oral	1/30
		Written	0/22
	Action naming	Oral	1/28
		Written	2/22
	Naming on verbal definition	Oral	1/16
Syntactic tasks	Grammatical decision	Auditory	3/48
		Written	4/24
	Transcoding tasks	Repetition	1/20
		Reading	0/6
	Sentence comprehension	Auditory	6/60
		Written	3/45

sentences. Repetition was still difficult for three-syllable non-words and four-syllable words. On this task, his errors were all phonological substitutions. In writing non-words and words to dictation, orthographic substitutions were still present. His ability to name nouns and actions both in the oral and in the written modalities was normal. His oral comprehension was impaired for complex commands (token test: 16/36, cut-off 29, Spinnler & Tognoni, 1987) and was still slightly impaired for sentences. On this task, he made few errors in the processing of reversible sentences (BADA test, Miceli et al., 1994) (see Table 1).

Since he worked as an accountant, he complained about his difficulty in number reading. Therefore, a series of tests were administered to investigate F.A.'s number reading in more detail.

2.2. Experimental investigation

2.2.1. Reading aloud Arabic numerals and written number words

The patient was asked to read a list of 70 Arabic numerals and the corresponding number words composed of 10 two-digit, 20 three-digit, 20 four-digit and 20 five-digit numbers. For Arabic numerals, F.A. made errors on all stimulus magnitudes, although with a larger proportion for four- and five-digit numerals (18 errors out of 40 stimuli (45%)). For number words, errors occurred only on four- and five-digit words (11 errors out of 40 stimuli (27.5%) (see Table 2). Accordingly, only four- and five-digit numbers were used as experimental stimuli for the following tests to maximise the occurrence of errors.

Table 2
F.A.'s number of errors in reading aloud Arabic numerals and the corresponding number words

Stimuli	Number of errors
Arabic numerals (two–three digits)	5/30
Number words (two–three digits)	0/30
Arabic numerals (four–five digits)	18/40
Number words (four–five digits)	11/40

2.2.2. Reading aloud four- and five-digit Arabic numerals and number words

A new set of 460 Arabic numerals (230 four- and 230 five-digit numbers) with the corresponding number words was administered to the patient. For four-digit numbers, 36 items included zeros (29 items with one zero and 7 items with two zeros). For five digits numbers, 41 items included zeros (32 items with one zero and 9 items with two zeros). The number of words forming verbal numerals was between 4 and 7.

Both the Arabic numerals and their corresponding number words were presented in a counterbalanced design (for a total of two testing sessions). The patient failed to read 84 out of 460 (18.3%) Arabic numerals (42 errors on four- and 42 on five-digit numbers) and 48 out of 460 (10.4%) number words (24 on four- and 24 on five-digit numbers). Considering his performance on the previous reading task, F.A.'s overall error rate was 20.4% for both four- and five-digit numerals (51 errors out of 250 stimuli for four-digit and 51 errors out of 250 stimuli for five-digit Arabic numerals). For four-digit number words, the overall error rate was 10.4% (26 errors out of 250 stimuli) and for five-digit number words it was 13.2% (33 errors out of 250 stimuli).

2.2.2.1. Error analysis. Analyses were performed on F.A.'s overall error rate both for Arabic numeral and number word reading. A first analysis showed that the patient made more errors in reading Arabic numerals than number words (102 errors out of 500 stimuli and 59 errors out of 500 stimuli, respectively, for Arabic numerals and number words reading) ($\chi^2 = 13.68$, $P < 0.001$). Both for Arabic numerals and number words, the error rate was the same for four- and five-digit numbers (the differences were non-significant for both classes of stimuli).

A second analysis was made according to Deloche and Seron's (1982) distinction between lexical and syntactic errors. Lexical errors concern one or more number elements and result in substitutions of numbers belonging to the same number-lexical class ("within-class, across position" errors, e.g. 63 > 69) or to a different class but in the same ordinal position ("across-class, within-position" errors, e.g., 912 > 920). Syntactic errors involve the assembling of the number structure (the syntactic frame; McCloskey, 1992) and typically consist of incorrect arrangements of multiplier words, resulting in a different number of words than the corresponding correct response (e.g., 27 > 207).

In Arabic number reading, the patient made 70 lexical errors (e.g. 7260 > 7268), 19 syntactic errors (e.g. 5429 > 500.429) and 13 mixed errors (both lexical and syntactic) (e.g. 51.821 > 400.821). In number words reading, the patient made 52 lexical errors (e.g. novemilacentonovantanove (9199) > duemilacentonovantanove (2199)), six syntactic errors (sessantottomilaottantacinque (68,085) > sessantottomilaottocentocinque (68,805)) and one mixed error (ottantatremilacinquecentoquattordici (83,514) > ottantatremilacinquecentoquarantacinque (83,545)). Both for Arabic number and number word reading, lexical errors were the most frequent (for Arabic numerals: $\chi^2 = 29.2$, $P < 0.001$ for lexical versus syntactic errors and $\chi^2 = 39.1$, $P < 0.001$ for lexical versus mixed errors; for number words: $\chi^2 = 36.5$, $P < 0.001$ for lexical versus syntactic errors and $\chi^2 = 49.1$, $P < 0.001$ for lexical versus mixed errors). Finally, the number of errors for the two classes of stimuli showed a significant difference for syntactic errors ($\chi^2 = 6.8$, $P < 0.01$) but not for lexical errors ($\chi^2 = 2.6$, n.s.). Table 3 reports the types of errors (lexical, syntactic and mixed errors) made on Arabic numbers and number words, respectively for four- and five-digit numbers.

To sum up, the error analysis showed a large predominance of lexical errors. The patient's overall performance was worse on Arabic numbers than on number word reading, but the main determinant of such difference was the greater number of syntactic errors in reading Arabic numbers. The more severe deficit in Arabic number reading can be attributed to the greater difficulty of the task. That is, reading Arabic numbers involves the construction of a syntactic frame that constitutes a plan for the production of the appropriate sequence of words (e.g., McCloskey, Sokol, & Goodman, 1986), whereas syntax is fully specified in the input in number word reading.

Table 3
Type, number and percentage (within parentheses) of errors made by F.A. in reading aloud four- and five-digit Arabic numerals and number words

	Lexical	Syntactic	Mixed	Total
Arabic numerals				
Four digits	33 (64)	9 (18)	9 (18)	51
Five digits	37 (72)	10 (20)	4 (8)	51
Total	70 (69)	19 (18)	13 (13)	102
Number words				
Four digits	24 (92)	1 (4)	1 (4)	26
Five digits	28 (85)	5 (15)	0	33
Total	52 (88)	6 (10)	1 (2)	59

It could be argued that the patient's errors are linked to his low memory span. However, the low span should have affected five-digit numbers more than four-digit numbers, which was not the case. Furthermore, the patient's errors always respected the length of the target stimuli in terms of number of digits and the incorrect responses were often longer than the correct ones in terms of number of phonemes (e.g. 32,777 > 34,775, trentaduemilasettecentosettantasette (32,777) > trentaquattromilasettecentosettantacinque (34,775); 39,805 > 39,850, trentanovemilaottocentocinque (39,805) > trentanovemilaottocentocinquanta (39,850). Finally, it is important to stress that an explanation of F.A.'s deficit in terms of low working memory span would not explain why the large majority of errors were lexical rather than syntactic and why errors were still made when the sequence of words to be produced was entirely available in the input (number word reading task).

2.2.3. Reading aloud words, non-words, compound pseudowords, syntagms and sentences

2.2.3.1. Reading words. Different lists of linguistic stimuli were administered to the patient to compare his ability to read linguistic materials with his number reading performance. The patient was first asked to read aloud 20 very long words (comprised of 17–22 phonemes), whose length was comparable to that of the four- and five-digit numbers (e.g. deresponsabilizzazione (avoiding one's responsibilities)). In this task, the patient made 12 phonological errors consisting of one phoneme transposition (e.g. approssimativamente (approximately) > approssivatimamente) and phonological approximations to the target (e.g. raccomandabilissimo (very recommendable) > accorandabilissimo ... accondarabilissimo ... raccomandabilissimo (very recommendable)).

2.2.3.2. Reading non-words. The patient was asked to read aloud 40 pronounceable, four- to five-syllable non-words. Twenty of the non-words were derived from real words by substituting two phonemes (e.g. campalario > lampadario (chandelier)), whereas the other 20 were invented non-words (e.g. crestobante). The patient made seven errors on the first list and six on the second list. On both tasks, errors were again all phonemic substitutions.

2.2.3.3. Reading compound pseudowords, syntagms and sentences. Since complex numbers, such as those with four-digit and five-digit, are supposed to be represented in a decomposed form in the lexicon as distinct and individual number names (e.g. 3440 > three-thousand-four-hundred and forty), the best comparison seemed to be with linguistic materials made up of different words that had the same length of the individual numbers in the number

Table 4
F.A.'s number of errors in reading aloud complex linguistic materials

Words (seven–nine syllables)	12/20
Non-words (derived) (four–five syllables)	7/20
Non-words (invented) (four–five syllables)	6/20
Compound pseudowords	10/20
Syntagms	9/34
Sentences	0/20

words used, combined into syntactically structured phrases. The patient was asked to read aloud 20 compound pseudowords (e.g. pneumocalzecontabiologico) and 34 syntagms (presidente della repubblica (president of the republic)). He made 10 errors on compound words and 9 errors on syntagms (e.g. pneumocalzecontabiologico > pneumocalzacontabiologico; presidente della repubblica (president of the republic) > presidente della repubblida). On both tasks, errors were all phonological substitutions.

Finally, the patient was presented with 20 sentences in which words were matched for frequency and length with the corresponding number words (e.g. stasera aspetta contento coi signori (this evening he is happily waiting with the gentlemen)). On this task, his performance was flawless (see Table 4).

To sum up, the patient's ability to read linguistic materials aloud was mildly impaired when using very long stimuli such as words, non-words, compound pseudowords and syntagms. When using sentences, his performance was flawless. However, it is interesting to note that errors with long stimuli were all phonological while number word reading was subject to frequent word substitutions (lexical errors) and, less frequently, to modifications of the syntactic structure of the stimuli (syntactic errors).

3. Number processing tests

A series of experiments were carried out to establish whether the F.A.'s number reading impairment reflected a deficit in the recognition and/or comprehension and/or production number systems. The four- and five-digit numbers used in all tasks were the same on which the patient had made reading errors. Results are summarised in Table 5.

3.1. Number recognition

Matching Arabic numerals with written number words. The patient was asked to match 10 Arabic numerals with their corresponding number words, which were presented together with two other alternatives. The patient made no errors.

Matching written number words with Arabic numerals. The patient was required to match 10 written number words with their corresponding Arabic numerals, which were presented together with two alternatives. Again, F.A.'s performance was flawless (see Table 5).

Both tasks were repeated with a delayed presentation of the response alternatives, which were showed to the patient after a 3 s time interval from the target stimulus. On these tasks, he correctly matched Arabic numerals to written

Table 5
F.A.'s number of errors in the different subtests of number processing

Number recognition	Matching Arabic numerals to written number words	0/10
	Matching written number words to Arabic numerals	0/10
Number comprehension		
	Visual Arabic numerals magnitude comparison	1/20
	Visual number words magnitude comparison	0/20
	Ordering three Arabic numerals by magnitude	0/20
	Ordering three number words by magnitude	0/20
	Written additions	1/20
Spoken and written number production		
Counting	Oral presentation > oral response	13/20
	Oral presentation > written response in Arabic code	0/20
	Written presentation in Arabic code > written response in Arabic code	0/20
	Written presentation in alphabetic code > written response in alphabetic code	0/20
What comes next	Oral presentation > oral response	5/20
	Oral presentation > written response in Arabic code	0/20
	Written presentation in Arabic code > written response in Arabic code	0/20
	Written presentation in alphabetic code > written response in alphabetic code	1/20
Personal and non-personal number facts	Oral presentation > oral response	4/12
	Oral presentation> oral response in Arabic code	0/12
Additions and subtractions	Oral presentation > oral response	10/20
	Oral presentation > written response in Arabic code	0/20
	Written presentation in Arabic code > oral response > written response in Arabic code	14/40 and 2/14

number names and made only one error in matching the number word with the corresponding Arabic numeral.

3.2. Number comprehension

Magnitude comparison with Arabic numbers. Twenty pairs of four- or five-digit Arabic numerals were visually presented to the patient. He was asked to point to the larger of the two numbers. He made only one error.

Magnitude comparison with written number words. Twenty pairs of four- or five-digit number words were visually presented to the patient. The patient was always able to point to the larger number word.

Ordering three Arabic numerals by magnitude. Twenty triplets of four- or five-digit numbers were presented and the patient was asked to reorder them according to their cardinal value (from the lowest to the highest). His performance was flawless.

Ordering three number words by magnitude. The same 20 stimuli of the previous task were used but in the corresponding alphabetical code. F.A. had to reorder the number words according to their cardinal value. Again, he made no errors.

Four- and five-digit additions. Twenty four- and five-digit addition problems were visually presented to the patient. He was asked to make the calculations and write the result. His performance was flawless (see Table 5).

To sum up, the results of the above tests demonstrated that the patient's ability to recognise and comprehend Arabic numerals and number words was largely intact. Therefore, his deficit in Arabic numbers and number word reading cannot be attributed to difficulties in recognising the stimuli or in accessing the semantics of numerals.

3.3. Spoken and written number production

3.3.1. Counting forward

Oral presentation > oral response. Oral presentation > written response in Arabic code. In this task, 10 four- and 10 five-digit numbers were orally presented to the patient, and for each number he was asked to count forward for the next 10 numbers. Stimuli were administered in two sessions. In the first session, the patient was asked to give an oral response for half of the stimuli and a written response in Arabic code for the other half. In the second session, for both modality (oral and written), the remaining half of the stimuli were tested. In the oral output modality, the patient failed 13 times on 20 stimuli (65%, 6 times on four-digit and 7 times on five-digit numbers), but he made no errors in the written output modality. Considering all errors made in the ten number sequences, 13 were lexical, 10 syntactic and 3 mixed. The difference between the two output modalities was significant ($\chi^2 = 19.25$, $P < 0.001$).

3.3.2. What comes next?

Oral presentation > oral response. Oral presentation > written response in Arabic code. The patient was orally presented with 10 four- and 10 five-digit numbers and for each number was asked to produce the next one in the oral or written output modality. The task was administered in two sessions. In the first session, the patient had to give an oral response for half of the stimuli and a written response for the other half. In the second session, for both modality (oral and written) the remaining half of the stimuli was tested. In the oral output modality, he made 5 errors on 20 stimuli (25%) (2 lexical, 2 syntactic and 1 mixed error), while in the written output modality his responses were all correct. The difference between the two output modalities was significant ($\chi^2 = 5.71$, $P < 0.01$).

3.4. Personal and non-personal number facts

Oral presentation > oral response. Oral presentation > written response in Arabic code. The patient was asked six questions about personal numerical information such as autobiographical dates (e.g., year of birth) and six questions about famous historical dates (e.g., the discovery of America). All of the questions required the production of four-digit spoken number names and written Arabic numbers. The task was administered in two sessions. In the first session, the patient was required to give an oral response for half of the stimuli and a written response in Arabic code for the other half. In the second session, for both modality (oral and written), the remaining half of the stimuli was tested. The subject made 4 errors (3 lexical and 1 syntactic errors) out of 12 responses in the oral modality and no errors in written output. Analysis showed a significant difference between the two output modalities ($\chi^2 = 4.8$, $P < 0.05$).

3.5. Calculation tests (additions and subtractions)

Oral presentation > oral response. Oral presentation > written response in Arabic code. The patient was presented with 10 additions and 10 subtractions. Both operations were formed by a first four- or five-digit number and by a second one-digit number (from 1 to 9). Each arithmetical problem was presented orally in pseudo-random order as an addition or a subtraction and the patient was asked to give either a spoken or a written response. The task was carried out in two sessions. In the first session, half of the responses were required in the oral modality and half in the written modality. In the second session, for both modality (oral and written), the remaining half of the stimuli was tested. He made 10 errors in the oral output modality (3 errors on additions and 7 errors on subtractions) and no errors in the written modality. Seven errors were lexical (5 errors for four-digit and 2 for five-digit numbers) and 3 were syntactic (2 for four-digit and 1 for five-digit numbers). The difference between the two output modalities was significant ($\chi^2 = 13.3$, $P < 0.01$) (see Table 5).

Written presentation in Arabic code > oral response followed by a written response in Arabic code. A second calculation task was administered to directly compare the two output modalities. In the case of an incorrect oral response, the patient was asked to give the corresponding written response in Arabic code. F.A. was presented with 10 additions and 10 subtractions. Both operations were formed by a first four- or five-digit number and by a second one-digit number (from 1 to 9). Each arithmetical problem was presented orally in a pseudo-random order as an addition or as a subtraction and the patient was asked to give a spoken response. If the patient gave an incorrect oral response, he had to write the result in Arabic code. In the oral modality, he made 14 errors (4 errors on additions and 10 errors on subtractions; 8 errors for four-digit and 6 for five-digit numbers). Ten errors were lexical and 4 syntactic. When asked to write the result for these 14 incorrect responses, he made only two errors (both lexical). The difference between the two output modalities was significant ($\chi^2 = 8.5$, $P < 0.005$) (see Table 5).

To sum up, the results of the above tests clearly showed that the patient had a selective difficulty in producing numbers only when the response required an oral output. His written responses were always correct in the Arabic code. Errors in the spoken output tasks were mostly lexical. Therefore, it seems likely that his difficulties in reading four- and five-digit numbers arise from a deficit in the spoken number name output system. In the next tests, we investigated whether his preserved ability to write also extended to number words.

3.6. Written number production

3.6.1. Counting forward

Written presentation in Arabic and alphabetic code > written response in Arabic and alphabetic code. The patient was visually presented with 10 four- and 10 five-digit numbers as Arabic numerals. For each number, he was asked to write the next ten numbers in Arabic code. The same stimuli were visually presented as number words and for each number word the patient was asked to write the next 10 numbers in the alphabetic code. Stimuli were run in two sessions. In the first session, half of the stimuli were presented in the Arabic and half in the alphabetic code. In the second session, the order of presentation was reversed. In both tasks, his performance was flawless.

3.6.2. What comes next?

Written presentation in Arabic and in alphabetic code > written response in Arabic and alphabetic code. The patient was visually presented with 10 four- and 10 five-digit numbers as Arabic numerals. For each number, he was asked to write the next one in the Arabic code. The same stimuli were visually presented as number words. For each stimulus, the patient was asked to write the next one in the alphabetic code. The stimuli were administered in two sessions. In the first session, half of the stimuli were presented in the Arabic and half in the alphabetic code. In the second session, the order of presentation was reversed. The patient made no errors in writing the numbers in Arabic code (20 out of 20 correct responses) and one error in number word writing (19 out of 20 correct responses) (see Table 5).

3.7. Number transcoding

From Arabic numbers to written number words and from written number words to Arabic numbers. Since the two previous tasks did not explicitly require the transcoding between number formats, the patient was also asked to transcode 10 four- and 10 five-digit written Arabic numbers into the corresponding written number words and vice versa. His performance was flawless.

To sum up, the results clearly confirmed that the patient's ability to process numbers in the written output modality was intact, both for Arabic numerals and number words.

4. Discussion

We described the case of a patient with a deficit in reading aloud multi-digit Arabic numbers and number words. His errors mostly consisted of lexical substitutions of one entire number word for another. In contrast, his ability to read linguistic materials was almost intact. On these tasks, he made errors only with very long stimuli, all consisting of phonological substitutions. The patient's ability to comprehend Arabic numerals and number words was largely preserved across a series of tasks, suggesting that his reading impairment could not be attributed to impaired access to number semantics. However, he selectively failed in all production tasks, but only when he was asked to give an oral response. Notably, his written responses were always correct both in the Arabic and alphabetic code. The dissociation between spoken and written output was particularly striking when the patient produced a correct written response to an arithmetic problem immediately following a wrong oral answer to the same problem.

Two main findings have to be interpreted. First, in light of current models of number processing (Cipolotti & Butterworth, 1995; Dehaene & Cohen, 1995; McCloskey, 1992), the level of the patient's number reading impairment needs to be explained. Second, the dissociation between his almost preserved ability to read linguistic materials and his impairment in number word reading also needs clarification.

As stated in Section 1, in McCloskey and colleagues' model (see McCloskey, 1992 for a review), different mechanisms are involved in the comprehension of Arabic numerals and number words. However, once the semantic representation of both stimuli is formed, the surface features of the number (whether the number is in Arabic or alphabetic script) have no effect on the subsequent production process. In the case of an output deficit, this leads to an equal impairment for Arabic numerals and number words on all production tasks. Nonetheless, this pattern of errors is also consistent with the triple code model of Dehaene

(1992) and Dehaene and Cohen (1995), where both Arabic and verbal numerals are converted into a common auditory-verbal code prior to the activation of the spoken output. The auditory-verbal code represents numbers as syntactically organised sequences of words (Dehaene & Cohen, 1995; following McCloskey, 1992).

According to McCloskey's (1992) model, a reading impairment for Arabic numerals and number words could arise from double damage to the number comprehension systems (to the Arabic numerals and number words components, respectively), or to the abstract semantic representations, or to the spoken number name output system. The results of the magnitude comparison tasks and the calculation tasks clearly showed that the patient's reading difficulties were not due to damage to the two comprehension components or to the semantics of numerals. In contrast, he had a selective difficulty in the spoken production of multi-digit numbers that affected not only the reading task but also all of his spoken answers to calculation and number naming tasks. Therefore, his reading impairment would be the result of a selective deficit in the spoken output system that equally affects reading of multi-digit Arabic numerals and number words. The multi-route model of Cipolotti (1995) and Cipolotti and Butterworth (1995) postulates the existence of asemantic transcoding routes for reading Arabic numbers and number words. The patient described by Cipolotti and Butterworth had difficulties in spoken production that affected only Arabic numerals and number word reading. Therefore, the authors proposed a modified version of McCloskey's (1992) model, hypothesising that their patient had double damage to two asemantic transcoding routes for the processing of Arabic numerals and number words, respectively. According to this view, two different types of impairment would be responsible for the observed pattern of performance in our patient: damage to the two asemantic transcoding routes, responsible for his difficulties in reading Arabic numerals and number words, and damage to the spoken output number name system, responsible for his errors in the calculation and number naming tasks. However, since he made errors in all output tasks, and they were not dependent on the format (Arabic versus alphabetic) in which the number was written, we believe that our patient's performance fits well with single selective damage to the spoken number name lexicon in McCloskey's model (or to the equivalent component in Dehaene's, 1992 triple code model).

A pattern of performance similar to that of F.A. has been reported for patient H.Y. by McCloskey et al. (1986). H.Y. showed an overall error rate of about 14% in reading a set of almost 5000 Arabic numbers. He made mostly lexical substitutions and his error rate was significantly higher for spoken responses than for written responses. The percentage of incorrect responses for four- and five-digit numbers was 26.2 and 28.3, respectively, which is of comparable size to that showed by F.A. Overall, H.Y.'s error rate tended to increase as a function of the number of digits (e.g., he made only 6.5% errors on two-digit numbers).[1] McCloskey and colleagues attributed H.Y.'s difficulties in reading numbers to a deficit in spoken verbal-number production. However, one crucial difference between the two patients is that H.Y. also exhibited significant language deficits: for instance, he scored 10 out of 60 on the Boston naming test (Goodglass & Kaplan, 1983) and showed a moderate-to-severe deficit in oral reading of words and sentences.

The impairment to the spoken verbal-number production system in F.A. affects both the selection of individual number words within the phonological lexicon, and (although to a lesser extent) the build-up of a syntactic frame. F.A. made mostly lexical errors, but syntactic errors were also present in all production tasks and for both Arabic numerals and number words (in number reading they represented 25% and 15% of the errors, respectively). As previously discussed, the presence of more syntactic errors for Arabic numbers than for number words could be attributed to the fact that the first requires a more complex process, because the (verbal) syntactic structure is fully specified in number word reading. In McCloskey's (1992) model, the same syntactic processing mechanisms are assumed to underlie processing of both spoken and written verbal numerals, whereas lexical processing distinguishes between phonological and graphemic processing mechanism (see Fig. 1). Similarly, the triple code model (Dehaene & Cohen, 1995) assumes that a single syntactic frame is linked to both phonological and graphemic forms of the word. Therefore, the production of spoken and written verbal numerals should diverge only at the lexical retrieval stage. Sokol and McCloskey (1988) studied a patient whose performance supported this assumption: J.S. made syntactic errors in both spoken and verbal written output but lexical errors were present only in his spoken responses. In other words, J.S. exhibited both a syntactic association and a lexical dissociation between the two output modalities. F.A., however, produced only one error across the three tasks that required the written production of four- and five-digit verbal numerals (counting forward, "what comes next", and transcoding from Arabic code). That is, the dissociation was present both at the lexical and syntactic level, suggesting a functional independence of the spoken and written verbal output systems even at the syntactic level.

Another intriguing observation is related to the dissociation between the patient's number word reading impairment and his almost preserved ability to read linguistic materials. Since words and number words share the same alphabetic code, in the absence of a semantic deficit we would expect errors to equally affect both types of stimuli. Instead, when matched by frequency and length, errors were made mostly on number words. Furthermore, in the case of number words,

[1] The number of errors made by F.A. in reading two- and three-digit Arabic numerals (see Table 2) would suggest a similar pattern. However, the number of items in this reading task was rather low. Unfortunately, we did not have the opportunity to test the patient on almost 5000 Arabic numbers as McCloskey et al. (1986) did.

errors were all lexical substitutions of one number word for another while rare phonological substitutions were made on linguistic material.

Cohen et al. (1997) reported a similar pattern of performance in their patient's word and number word reading impairment. Errors in reading words were all phonological, whereas in reading number words the patient made only lexical errors. As discussed in Section 1, the authors offered three possible interpretations for the dissociation between words and number words: (i) a category-specific effect reflecting a categorical organisation that extends from the semantic to the phonological level; (ii) number words are over-learned word series, produced as automatic speech; (iii) number words behave as entire phonological entities, similar to acronyms. Since our patient did not show any difficulty in the processing of automatic speech and his ability to read acronyms was not tested, we will refer to their first interpretation. In accordance with Levelt's (1992) model of speech production, Cohen and colleagues hypothesised that words are organised according to their categorical domain down to the lexical/phonological level. In their patient, the activation of phonemes from number words was unimpaired, whereas the activation of the same phonemes from words of other categorical domains was damaged.

Our results exclude the possibility that F.A.'s number production deficit arises at the semantic level. Errors were mostly lexical and they were present only in the oral production tasks. Together with his word reading performance, in which errors were very few and all phonological, F.A.'s pattern of performance further supports the hypothesis that words and numbers are subserved by different processing mechanisms even at the lexical/phonological level.

References

Albert, M. L., Yamadori, A., Gardner, H., & Howes, D. (1973). Comprehension in alexia. *Brain*, *96*, 317–328.

Anderson, S. W., Damasio, A. R., & Damasio, H. (1990). Troubled letters but not numbers: domain specific cognitive impairments following focal damage in frontal cortex. *Brain*, *113*, 749–766.

Basso, A., & Beschin, N. (2000). Number transcoding and number word spelling in a left-brain-damaged non-aphasic acalculic patient. *Neurocase*, *6*, 129–139.

Basso, A., Capitani, E., & Laiacona, M. (1987). Raven's coloured progressive matrices: normative values on 305 adult normal controls. *Functional Neurology*, *2*, 189–194.

Butterworth, B., Cappelletti, M., & Kopelman, M. (2001). Category specificity in reading and writing: the case of number words. *Nature Neuroscience*, *4*, 784–785.

Cipolotti, L. (1995). Multiple routes for reading words, why not numbers? Evidence from a case of Arabic numeral dyslexia. *Cognitive Neuropsychology*, *12*, 313–342.

Cipolotti, L., & Butterworth, B. (1995). Toward a multiroute model of number processing: impaired number transcoding with preserved calculation skills. *Journal of Experimental Psychology: General*, *124*, 375–390.

Cipolotti, L., Butterworth, B., & Denes, G. (1991). A specific deficit for numbers in a case of dense acalculia. *Brain*, *114*, 619–637.

Cipolotti, L., Warrington, K. E., & Butterworth, B. (1995). Selective impairment in manipulating Arabic numerals. *Cortex*, *31*, 73–86.

Cohen, L., Verstichel, P., & Dehaene, S. (1997). Neologistic jargon sparing numbers: a category-specific phonological impairment. *Cognitive Neuropsychology*, *14*, 1029–1061.

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition*, *44*, 1–42.

Dehaene, S., & Cohen, L. (1995). Towards an anatomical and functional model of number processing. *Mathematical Cognition*, *1*, 83–120.

Delazer, M., & Bartha, L. (2001). Transcoding and calculation in aphasia. *Aphasiology*, *15*, 649–679.

Delazer, M., & Girelli, L. (1997). When 'Alfa Romeo' facilitates 164: semantic effects in verbal number production. *Neurocase*, *3*, 461–475.

Deloche, G., & Seron, X. (1982). From three to 3: a differential analysis of skills in transcoding quantities between patients with Broca's and Wernicke's aphasia. *Brain*, *105*, 719–733.

Goodglass, K., & Kaplan, E. (1983). *The Boston naming test*. Philadelphia, PA: Lea and Febiger.

Hécaen, H., & Kremin, H. (1976). Neurolinguistic research on reading disorders resulting from left hemisphere lesions: aphasic and 'pure' alexia. In H. Whitaker, & H. A. Whitaker (Eds.), *Studies in neurolinguistic*. New York: Academic Press.

Levelt, W. J. M. (1992). Accessing words in speech production: stages, processes and representations. *Cognition*, *42*, 1–22.

McCloskey, M. (1992). Cognitive mechanisms in numerical processing: evidence from acquired dyscalculia. *Cognition*, *44*, 107–157.

McCloskey, M., Sokol, S. M., & Goodman, R. A. (1986). Cognitive processes in verbal-number production: inferences from the performance of brain-damaged subjects. *Journal of Experimental Psychology: General*, *115*, 307–330.

Miceli, G., Laudanna, A., Burani, C., & Capasso, R. (1994). *Batteria per l'analisi dei deficit afasici, BADA*. Cepsag, Università Cattolica del Sacro Cuore Policlinico Gemelli.

Noel, M. P., & Seron, X. (1993). Arabic number reading deficit: a single case study or when 236 is read 2306 and judged superior to 1258. *Cognitive Neuropsychology*, *10*, 317–339.

Orsini, A., Grossi, D., Capitani, E., Laiacona, M., Papagno, C., & Vallar, G. (1987). Verbal and spatial immediate memory span: normative data from 1355 adults and 1112 children. *The Italian Journal of Neurological Sciences*, *8*, 539–548.

Sokol, S. M., & McCloskey, M. (1988). Levels of representation in verbal number production. *Applied Psycholinguistics*, *9*, 267–281.

Spinnler, H., & Tognoni, G. (1987). Standardizzazione e taratura italiana di test neuropsicologici. *The Italian Journal of Neurological Sciences*, *6*, 1–120.

Thioux, M., Pillon, A., Samson, D., De Partz, M. P., Noel, M. P., & Seron, X. (1998). The isolation of numerals at the semantic level. *Neurocase*, *4*, 371–389.