Inversion Errors in Arabic Number Reading:
Is There a Nonsemantic Route?

G. Blanken, M. Dorn, and H. Sinn

Research Program in Neuropsychology and Neurolinguistics,
University of Freiburg i. Br., Freiburg, Germany

This article reports on a mildly aphasic patient with major disorders in reading, writing, and number processing. His predominant error type in reading aloud Arabic numbers and in matching heard numerals with Arabic numbers was the violation of the inversion rule of the German Arabic number reading system. According to this rule most of the two-digit numbers or numbers in the final and prefinal position of longer digit strings have to be read beginning with the final digit (e.g., 26 → sechsundzwanzig (literally translated: six-and-twenty)). It is argued that AT’s inversion errors (e.g., 26 → zweiundsechzig (literally translated: two-and-sixty)) are not consistent with the predictions of single route models of Arabic number reading but are in agreement with proposals of a visually based asemantic reading routine in addition to a semantically mediated reading routine.

INTRODUCTION

Most educated and healthy individuals are able to read Arabic numerals as fluently as they read alphabetical symbols. Indeed, many books and articles, including this one, integrate letters and digits being confident in this competence of the skilled reader. However, in cases of brain damage the affected individuals can find themselves confronted with rather specific difficulties in coping with one or the other code (see Henschen, 1920; Kleist, 1934; Hécaen, Angelergues, & Houllier, 1961). Meanwhile, dyslexic disorders for words as well as for Arabic numbers have been extensively studied by psychologists and linguists who are interested in their implications for the nor-
mal reading process (see for recent reviews, e.g., Kay, 1993; McCloskey, 1992; Dehaene & Cohen, 1995).

With respect to the verbal domain, it is a widely—though not generally—accepted hypothesis that for reading aloud we have to distinguish not only between components of visual input, phonological output, and semantic processing but also between a lexicosemantic and a nonlexical pathway (see, e.g., Coltheart, Curtis, Atkins, & Haller, 1993). This dual-route hypothesis corresponds well to the neuropsychological claim of mainly two different types of central reading dysfunctions: reading for meaning and reading for sound. While patients of the latter type—the so-called “surface dyslexics”—typically pronounce written words (including irregular ones; e.g., sub-tle) by sounding them out instead of retrieving their semantically and lexically correct name, patients of the former type demonstrate a marked loss of their ability to use such print to sound rules. As a consequence, they are almost totally unable to read nonsense words or unfamiliar real words. Some of these cases, the “phonological dyslexics”, can fairly well rely on their acquired reading vocabulary, others seem to approach words by a more troublesome strategy which is based on the extraction of the targets’ meaning leading to many semantically related reading errors among other error types, a disorder known as “deep dyslexia” (see for more details the contributions in Coltheart, Patterson, & Marshall, 1980, and Patterson, Marshall, & Coltheart, 1985). In addition, a third reading route—supposedly spared in “direct dyslexia”—has been proposed that is thought to directly connect the visual input lexicon with the phonological output lexicon bypassing semantics (see, e.g., Schwartz, Saffran, & Marin, 1980; Lytton & Brust, 1989; however, see also the summation hypothesis of Hillis & Caramazza, 1991).

Also in the field of number dyslexia, considerable progress has been made during the past 10 years or so. Detailed case studies of brain-damaged patients were able to demonstrate that number processing can also be disturbed by relatively selective deficits due to damage to different functional subsystems. In order to achieve a principled account for the numerous patterns of deficits, McCloskey and his collaborators have proposed a comprehensive model of cognitive numerical processing (see McCloskey, Caramazza, & Basili, 1985; McCloskey, 1992; see Fig. 1). It comprises functionally autonomous input and output components specifically devoted to Arabic numbers and to verbal numerals. Furthermore, each input/output component is equipped with lexical and syntactic mechanisms that are able to process number identities as well as relational aspects between them, respectively. However, while the componential structure holds some similarity to models of word reading and writing the model is clearly a single-route model, that is, the translation from input to output between all four components is exclusively mediated through a central system of semantic number representations (see also Macaruso, McCloskey, & Aliminosa, 1993).

Alternative proposals on deriving words from digits have been suggested:
Deloche & Seron (1987) described a detailed “transcoding algorithm” which consists of sets of formal translation rules between the input and output modality (only written modalities are treated by the authors) without any semantic mediation. The basic idea of their proposal, namely, that first a recognition of digit frames has to take place which is then followed by rule-governed syntactic and lexical slot-and-filler operations, has been integrated into other models of number processing. Cohen and Dehaene (1991) also followed this general notion in their model of asemantic Arabic number reading, however, allowing for incremental conversion procedures based on successive access to syntactic and lexical information about the visual number forms (see Discussion for more details). Figure 2 shows a simplified version.
of the ‘‘triple-code model’’ (after Dehaene & Cohen, 1995; see Dehaene, 1992, for the full model). The model postulates three components of mental number representations: ‘‘verbal word frames’’, ‘‘visual arabic number forms’’, and ‘‘magnitude representations’’ (or number meanings). The components are interconnected by pathways that allow numerical information to be transcoded from each format into any other format of representation. Thus, the model explicitly postulates transcoding mechanisms which bypass semantic number representations.

The question of whether reading aloud Arabic numbers is exclusively achieved by a single meaning-based production mechanism or whether it can be brought about by more than one pathway—as postulated by the triple-code model—is still a highly disputed issue. Only but very recently a single case study conducted by Cohen, Dehaene, & Verstichel (1994) could introduce interesting data into this ongoing debate. They report on a mildly impaired aphasic French patient whose written language performance presented with a deep dyslexic disorder that extended to Arabic numbers. The patient demonstrated marked familiarity effects in reading both words and Arabic numbers. Semantic substitutions, a central symptom of deep dyslexia, did not only occur in word reading but also in number reading; e.g., the target ‘‘1918’’ was read aloud as ‘‘nineteen hundred and forty’’ (= year of the German attack on France) but correctly commented by saying ‘‘The end of World War I’’, thus expressing successful visual comprehension. Indeed, several number comprehension experiments confirmed that the patient’s visual access to semantics was unimpaired. However, as with unfamiliar words and nonwords he performed very poorly on reading aloud digit strings that were meaningless to him. His responses to these latter items consisted mainly of omissions or attempts to detect familiar number combinations within the target (e.g., the zip code of Marseille (= 13) in 1387). According to Cohen et al. the apparent analogies between the ‘‘deep’’ symptoms in word reading and the pattern in number reading can provide clear evidence against any single-route model and can give strong support to the assumption of a ‘‘surface’’ route of number reading (that was compromised in their patient).

The rules of visual Arabic number comprehension are organized universally on a strict left-to-right positional basis, i.e., in multidigit numbers each digit rises for the factor of 10 from right to left. However, languages differ as to how Arabic numbers are named or read aloud. Some languages (e.g., German, Dutch, and Arabic) do not consistently spell out numbers from left to right (as, e.g., English). Instead, some numerals have to be named in the reverse order compared to the Arabic numbers. This particularity holds in German for most two-digit numbers and for prefinal and final elements of longer digit strings. Thus, ‘‘48’’ and ‘‘52’’ are read as ‘‘achtundvierzig’’ and ‘‘zweiundfünfzig’’, respectively (literally translated as ‘‘eight-and-forty’’ and ‘‘two-and-fifty’’). Henceforth, we will refer to this particularity of verbal number processing in German as the inversion rule. Excluded from
this rule are all complex numbers with a ‘‘0’’ in the final (e.g., 40 or 110) or prefinal position (e.g., 103 or 2305)).

Violations of the inversion rule by brain-damaged patients have already been described in the German literature. Especially in the older neuropsychological literature case descriptions on this peculiar symptomatology can be found for reading (see Peritz, 1918, cases 4 and 6) and for writing to dictation (see Sittig, 1921). So-called position errors have furthermore been discussed by Kleist (1934) in the context of number alexia and number agraphia and have also been found in contemporary procedures of diagnosing brain-damaged patients with number processing disturbances (see Claros Salinas & von Cramon, 1987).

In the present paper the patient AT is described who exhibited frequent errors in reading aloud Arabic numbers. His predominant error type consisted of violations of the inversion rule of the German number reading system, that is, he read e.g., 28 as “zweiundachtzig” (eighty-two). In contrast, his visual number comprehension was better retained and there were no inversion errors in his semantic number comprehension. It is argued that AT’s inversion errors in reading aloud are due to impaired connections between the visual input component for Arabic numbers and the verbal output component bypassing semantics. We suggest that the case of AT can provide evidence in favor of a dual-route model of reading Arabic numbers.

PATIENT AT

AT is a 54-year-old right-handed man. In June 1991, at the age of 50, he suffered a cerebrovascular accident in the territory of the left middle cerebral artery. A CT scan (February, 1994) showed an area of hypodensity involving parts of the left superior temporal and the angular gyrus. Furthermore, consecutive widening of the left lateral ventrical and the left cortical sulci was noted. The stroke left him with a right hemiparesis, a right homonymous hemianopia, and a moderate aphasis language disorder with relatively preserved auditory comprehension. Reading and writing proved to be severely disturbed, however. In addition, problems with verbal short-term memory and with number processing were reported. In the following months the patient underwent intensive speech therapy and his language performance showed good recovery. In March 1992 he was assessed with the Aachen Aphasia Test (Huber et al., 1983). At that time his pattern of performance was consistent with the diagnosis of amnesic aphasia.

In October 1992 we began to see the patient regularly in our neurolinguistic laboratory. At that time the aphasic disorder had almost completely resolved. He was able to communicate his ideas fluently with only few word-finding difficulties. His oral language skills had evolved so far that he could act independently within his social community. However, the patient complained about major problems with reading, writing, and number processing.
One focus of investigation lay on his reading performance (see Sinn & Blan-ken, submitted). His writing disorder was assessed in much less detail (partly due to his motor disorder that made handwriting very strenuous for him). The present paper is dealing with his deficit in number processing. The data reported here were collected between June and December 1993.

It is important to note that potential premorbid deficiencies both in written language knowledge and in number processing could be excluded. AT attended school for 13 years followed by a 4-year university-level study (Fachhochschule). Before his illness he held a responsible position as an official in the regional school administration. His job responsibilities included reading, typing, and calculations on a high standard. Although AT, a native speaker of German, had learned some English and French at school (more than 30 years ago) he neither spent longer periods of time in foreign countries nor was his competence in other languages part of his job responsibilities so that interferences with, e.g., the English or French number reading system can be ruled out for AT.

**BACKGROUND INVESTIGATIONS**

Clinical neuropsychological examinations did not reveal any higher cognitive deficits apart from language (including written language) and number processing. On the HAWIE-R intelligence test (German version of the WAIS; Tewes, 1991), AT had an IQ of 86, scoring higher on the nonverbal (94) than on the verbal (84) section. His problems in number processing, block design, object assembly, and digit-symbol could be sufficiently explained by his aphasic, acalculic, and motor impairments. AT’s visual span was 5 as measured by the Corsi-tapping board. On the “Standard Progressive Matrices” (Raven, 1958) he reached a percentile rank > 75. There were no clinical signs of visual neglect.

AT’s picture naming abilities were only mildly impaired. In naming 118 morphologically simple targets including one to four syllabic words of different frequency levels (93 items < 100, 25 items > 100; frequencies controlled after Meier, 1967) 13 errors were made that were always semantically closely related to the target except for one word finding blockage. The picture naming task also included 101 two to five syllabic nominal compounds (noun–noun compounds, e.g., Papierkorb ((waste-)paper basket); frequencies < 100). All pictures referring to mono- and polymorphemic targets were presented in random order. In 63/101 responses AT was able to correctly name the depicted object by the target compound. There were 22 elaborations and attempts to approximate the target of which 14 were successful. Furthermore, eight simplifications occurred (only one component of the compound was named). Eight other errors were noted, four of them were substitutions of one of the target components (for the results of further patients and control subjects, see Blanken, in preparation). It is important to note that no inversion
TABLE 1
Results on the Age Estimation Task for AT and Nine Control Subjects
(Median Values and Ranges; Listed According to Increasing Age)

<table>
<thead>
<tr>
<th>AT Controls (median and range)</th>
<th>AT Controls (median and range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 21 (14–28)</td>
<td>56 54 (43–60)</td>
</tr>
<tr>
<td>25 27 (20–32)</td>
<td>62 62 (53–66)</td>
</tr>
<tr>
<td>33 32 (27–41)</td>
<td>63 53 (45–57)</td>
</tr>
<tr>
<td>36 28 (23–36)</td>
<td>63 60 (55–66)</td>
</tr>
<tr>
<td>42 42 (37–44)</td>
<td>63 73 (68–85)</td>
</tr>
<tr>
<td>42 42 (37–48)</td>
<td>65 65 (62–68)</td>
</tr>
<tr>
<td>43 32 (28–38)</td>
<td>65 65 (56–72)</td>
</tr>
<tr>
<td>43 48 (41–56)</td>
<td>65 65 (59–74)</td>
</tr>
<tr>
<td>43 50 (45–57)</td>
<td>65 68 (60–75)</td>
</tr>
<tr>
<td>45 40 (35–48)</td>
<td>65 68 (59–81)</td>
</tr>
<tr>
<td>53 56 (43–65)</td>
<td>65 72 (63–82)</td>
</tr>
<tr>
<td>53 59 (52–63)</td>
<td>68 73 (67–79)</td>
</tr>
<tr>
<td>53 70 (53–77)</td>
<td>73 70 (64–75)</td>
</tr>
<tr>
<td>55 60 (58–71)</td>
<td>82 72 (60–86)</td>
</tr>
<tr>
<td>55 65 (56–67)</td>
<td>83 74 (71–84)</td>
</tr>
</tbody>
</table>

errors in producing compounds were observed in AT (e.g., finger-nail → nail-finger). Indeed, there was no evidence that his tendency to invert morphological components in reading Arabic numbers was also present in producing compound words outside the number domain.

In order to test AT’s ability to produce verbal numerals he was asked to estimate the age of 30 faces depicted by photographs cut out from magazines. Seven of the depicted persons were relatively famous (politicians; sportsmen), the others were anonymous. Younger and older people were included. The pictures were glued on sheets of paper and were shown to AT one-by-one in random order. AT’s task was to estimate the age of the shown faces in years as exactly as possible. The same task was given to nine healthy control subjects (age: median 34, range 26–49; sex: five women, four men).

The results are given in Table 1. In 24/30 of his estimates AT fell within the range of the healthy subjects. In three cases his decisions differed only slightly (by 1, 2, or 3 years) from at least one of the controls which is—given the span of the controls’ estimates—negligible. In three cases he differed by 5 or 6 years from the decision of at least one of the controls (43 instead of 38, median 32; 63 instead of 57, median 53; 63 instead of 68, median 73).

We do not want to claim completely preserved capacities in estimating people’s age for the brain-damaged individual AT. However, most of his estimates were within the range of the controls and none of them was clearly inappropriate. Most importantly, inversion errors did not occur in this semantically guided estimation task. Inversion errors should be identifiable in this task because misordered number words would often lead to grossly deviant
Concerning AT’s three mostly deviating estimates, a reversion of the figures would have been fully inappropriate semantically in the last two cases. Given AT’s level of performance we can exclude that he would judge an about 70-year-old and an about 53-year-old person as having the age of 36, respectively. Only one of the thirty estimates (43) is potentially reconstructable by inversion since the inverted number is closer to the decisions of the controls. However, also in this case AT’s estimate was not fully deviant but differed only by 5 years from one of the controls.

Repetition of words and number words was relatively spared. AT performed flawlessly in repeating 40 randomly presented number words referring to two-to-three digit numbers (including all teens, 20 two-digit numbers where the inversion rule has to be applied in reading and 10 three-digit numbers ending with teens or tens).

In contrast, reading aloud of words and number words was severely restricted. In reading alphabetically presented zeros and ones he made few errors (16/20 correct) but with the teens his performance dropped markedly (8/20 correct). He failed consistently in reading composed verbal numerals like “sechsundzwanzig” (twenty-six; literally: six-and-twenty). In none of his attempts at reading these number words inversion errors were noted. Instead, he began to approximate the target by a left-to-right strategy (e.g., “sechsundzwanzig” (26) → sechzig hundert sechshundert sechs sechs sechsund zwanzig sechsundzwanzig; literally: sixty hundred sixhundred six six six and twenty six-and-twenty).

Further investigations of AT’s reading performance could provide evidence for the involvement of relatively early visual deficits in his dyslectic disturbance (Sinn & Blanken, submitted); e.g., in a same/different judgement task AT was asked to decide on 96 noun pairs (48 same/48 different) which were matched for length (four letters) and frequency. In addition, the same experiment was run with 96 four-digit Arabic numbers and 96 nonlinguistic four-item symbol strings (e.g., asterices, circles, etc.). In each of the “different” conditions of the three stimulus classes (n = 48 each) only one element was nonidentical, which was balanced over the four positions of the strings. In each of the tasks the order of presentation was random. In a timed version of the tasks (exposure duration 2 sec) numerous errors occurred with about the same proportions in the linguistic and the two nonlinguistic tasks (nouns 22/96; Arabic numbers 19/96; symbols 33/96). The occurring errors were largely restricted to the different conditions (nouns 20/48; Arabic numbers 18/48; symbols 24/48). No position effects became evident. In the untimed condition he performed flawlessly with the nouns and digits (the symbols were not presented in the untimed condition). This pattern is consistent with a relatively early visual input impairment involving the visual recognition of linguistic and nonlinguistic materials.

This deficit, however, cannot explain AT’s inversion errors in reading Ara-
bic numbers. Even if he could identify and name all digits of a presented number, inversion errors could still occur. Further arguments against an early visual account of his inversion errors are given below.

## EXPERIMENTAL INVESTIGATIONS IN ARABIC NUMBER PROCESSING

### Reading Aloud of Arabic Numbers

During several testing sessions, AT was asked to read aloud a total of 150 Arabic numbers. The presentation of the items was untimed. The first two item lists (reading I and II) consisted of Arabic numbers which referred to elementary number words. The last list (reading III) included compound targets that had to be composed of two morphemes. Henceforth, we refer to them as inversion items since for these targets the inversion rule has to be obeyed (see Table 2 for the results).

**Reading (I).** AT was required to read aloud a randomized list comprising all ones (0–9) and teens (10–19). Each number was represented twice. All targets could be named by a single elementary verbal numeral (e.g., 18 → achtzehn (eighteen)). The order of presentation was random except for the following rules: between same items at least four other items were interspersed; second, no more than two targets of the same class (ones/teens) in a row were given; third, consecutive items including a same digit (e.g., 17 followed by 7) were avoided.

AT made 4/40 errors. There were 3 substitution errors (17 → 12; 17 → 14; 16 → 19). All of them were immediately corrected by AT. In a further error he read 7 as 12. This error may have been triggered by the previous item 11 that he had read correctly.

**Reading (II).** AT was presented with all numbers up to 9000 that could be referred to by elementary verbal numerals (e.g., all ones (0–9), teens (10–19), tens (20, . . . , 90), hundreds (100, . . . , 900), and thousands (1000, . . . , 9000)). The list was randomized under the restriction that consecutive targets were not of the same class (e.g., teens, etc.) and did not begin with the same first digit.

AT made 12/46 errors. In one error he read 8 as 800. The previous item had been 600 so that perseverative mechanisms may have contributed to this error. The error may have been triggered by the previous item 11 that he had read correctly.

**Reading (III).** AT was presented with all numbers up to 9000 that could be referred to by elementary verbal numerals (e.g., all ones (0–9), teens (10–19), tens (20, . . . , 90), hundreds (100, . . . , 900), and thousands (1000, . . . , 9000)). The list was randomized under the restriction that consecutive targets were not of the same class (e.g., teens, etc.) and did not begin with the same first digit.

On this test AT made 12/46 errors. In one error he read 8 as 800. The previous item had been 600 so that perseverative mechanisms may have contributed to this error. The error was immediately corrected. Perseveration seemed to play a role in 6 further errors. The first teen in the list was 14. After having named it correctly he later perseverated this response with the targets 16, 19, 17, and 12. Also, trying to name 40 he responded by “14 uh 40” and with the target 20 he started with 4 but directly interrupted and corrected himself. The 5 remaining
errors were nonperseverative and in all cases he finally gave the correct response (30 → 300, 60 → 160, 70 → 7, 7, 7; 700 → 60, 70, 700; 600 → 300, 600; 8000 → 600, 700, 800, 8000).

Reading (III). This time AT was asked to read an item list ranging from 20 to 99. The series of sixties and seventies were given completely (e.g., 60, . . . , 69; 70, . . . , 79). For all other series (twenties, thirties, etc.) AT was confronted with the respective tens (e.g., 20) and three randomly selected numbers (e.g., 24, 26, 29). In addition, all ones and teens were included in the list. The list was randomized with the restriction that same digits in consecutive items were avoided. The task was constructed in order to assess AT’s ability to produce verbal numerals which have to be composed by more elementary items in an inverted order compared to the Arabic number (e.g., 26 → sechsundzwanzig (literal translation: six-and-twenty)).

As Table 2 shows, only two errors occurred with the elementary items. Both targets (teens) were finally correctly named in approximative sequences (12 → “zwei, elf, zehn, elf, zwölff” (two, eleven, ten, eleven, twelve); 16 → “vier, sechs, sechzehn” (four, six, sixteen)). In contrast, his reading of the inversion items was very poor. Table 3 gives a classification of AT’s responses with these targets and examples of the subtypes. There were only two spontaneously correct responses and further 10 reactions that resulted in correct responses after successive attempts at naming the target. Only in one case no response was possible (omission). In 15 of the 36 targets AT produced inversion errors. Eight of them were produced spontaneously and 7 after attempts to approximate the target by naming the first and/or the second position of the two-digit number. In 8 further cases he did not succeed in naming the number correctly despite several attempts of approximation resulting in other than inversion errors. In 5 of these cases he started with the left-most figure (e.g., 52 → five and . . .) indicating the same erroneous reading approach as in his complete inversion errors. In sum, problems with the inversion rule in German seem to lie at the heart of AT’s reading impairment of Arabic numbers.

**Multiple Choice Matching Task of Auditory Verbal Numerals to Arabic Numbers**

In this multiple choice matching task AT was presented with an auditory verbal numeral and a card representing four Arabic numbers. AT was required to first listen to the auditory stimulus (read aloud by the experimenter), then to repeat the heard word and finally to tick
TABLE 4
Number of Errors on a Verbal to Arabic Numeral Multiple Choice Matching Task in AT (52 items)

<table>
<thead>
<tr>
<th>Auditory stimuli</th>
<th>Matching errors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( N )</td>
</tr>
<tr>
<td>Two-digit numbers (excluding teens and tens)</td>
<td>24</td>
</tr>
<tr>
<td>Three-digit numbers (excluding teens)</td>
<td>9</td>
</tr>
<tr>
<td>Three-digit numbers (with zeros in final or middle position; e.g., 860)</td>
<td>10</td>
</tr>
<tr>
<td>Three-digit numbers (with teens; e.g., 216)</td>
<td>9</td>
</tr>
</tbody>
</table>

the corresponding Arabic number on the card. Targets were formed by 24 two-digit numbers (excluding teens and tens) and 18 three-digit numbers. Half of the latter ones had teens (11 to 19) in the last two positions (e.g., 217). None of these 42 items had the digit zero. Ten further three-digit items were included in the list with half of them having a zero in the final position (e.g., 860) and the other half in the middle position (e.g., 209). The 52 targets covered all classes of magnitude.

Besides the target (e.g., 147) there were three two- to three-digit distractors on each card: a distractor with a reversed order of the position of the ones and tens (e.g., 174) and two distractors showing a visual/phonological relationship to the target (e.g., 107, 140). The target position on the card (e.g., upper left, etc.) was balanced over all items. The position of the distractors and the order of presentation of the stimuli were randomized.

AT had no problems with the repetition of the heard stimuli. In the matching task, 14/52 errors occurred (see Table 4). Only one error was not based on digit order reversals (912 \( \rightarrow \) 911). Thus, also in matching spoken numerals to Arabic numbers impaired access to the correct order of the digit series formed the predominant feature of AT’s performance. However, while the errors with those two- to three-digit numbers in which teens were excluded were of the type described above, that is, the positions for the tens and ones were reversed (e.g., 76 \( \rightarrow \) 67; 498 \( \rightarrow \) 489), previously undetected error types occurred with items including teens and zeros. Indeed, in four matching errors zero position exchanges were evident (e.g., 508 \( \rightarrow \) 580) and on two occasions errors with teens occurred (113 \( \rightarrow \) 131; 416 \( \rightarrow \) 460).

As an account, we suggest that AT’s inversion errors in matching spoken numerals to Arabic numbers were based on a phonological mapping strategy. He repeated the verbal numerals morpheme by morpheme and compared the series of the spoken components with the number names parsing the digit strings from left to right. This sound-based strategy cannot only predict his “classical” inversion errors but also the problems with some teens and zeros; e.g., on a left-to-right basis the repeated sound-form “hundertdreizehn” (113) (literally: hundred-three-teen) is rendered better by 131 (hunderteinunddreißig; literally: hundred-one-and-thirty) than by the target itself since 131 corresponds to the actual order of mention of the components. However, inversion errors with the teens occurred only twice. The fact that inversion errors occurred only very rarely with the teens may be connected with their morphological structure. In German, the verbal numerals for 10, 11, 12 are monomorphemic (zehn, elf, zwölf). The numbers 13 through 19 are expressed by bimorphemic words (dreizehn, . . . , neunzehn), which are inverted (as in English). Furthermore, the mor-
zeros the same left-to-right strategy can account for 3/4 instances. All three targets (e.g., 209, zweihundertneun; literally: two-hundred-nine) had zeros in the middle position and were matched with choices with exchanged final positions (e.g., 290, zweihundertneunzig). A piece-meal strategy from left-to-right arrives at an acceptable mapping between the number word and the distractor item except for the last position. It is possible that AT acted too fast in his decisions and did not analyze the choices in sufficient detail. One last error is not well accounted for by our suggestion. With the target 860 (achtundsechzig) AT chose the distractor 806 (achtundsechs, literally: eight-hundred-six). This error does not fit into our account because there is no complete phonological overlap between the two verbal realizations of the figure 6 in both numerals. The 60 (sechzig, sixty) is pronounced /'zɛtsik/ while the 6 (sechs, six) is phonetically produced as /zɛks/. Given a phonological strategy this error is not clearly predictable. On the other hand there is some phonological similarity between the figures involved and one could argue that in this error instance the proximity was sufficient to induce this error. We do not know.

Yes/No Matching Task of Auditory Verbal Numerals to Arabic Numbers

In order to further investigate AT’s processing capacities of teens and tens AT was given another matching task. This time he was required to simply decide whether the auditorily presented number word matched with the visually presented Arabic numeral or not. AT was asked to express all positive decisions by ticking the corresponding Arabic number. Only two-digit numbers were used. There were two lists of matching stimuli. The first one excluded teens and tens (e.g., vierundfünfzig (54; literally: four-and-fifty) → 54); the second one consisted of teens and tens only (e.g., vierzehn (14; fourteen) → 14; fünfzig (50; fifty) → 50; half of each class). There were two lists of nonmatching stimuli. In the first one, the Arabic digits were arranged in the reversed (wrong) order compared to the graphic form of the auditory stimulus (e.g., zweiundsechzig (62; literally: two-and-sixty) → 26). Neither teens nor tens were part of this item group. The second list consisted of nonidentical stimulus pairs in which tens or teens or both were involved (e.g., neunzig (90; ninety) → 19). All pairs shared at least one digit. In seven cases the digits were identical but reversed (einundvierzig (41; literally: one-and-forty) → 14). All stimuli were given in random order. For correct decisions only the matching Arabic numbers were supposed to be ticked. However, we expected matching errors at least for the inverted condition. His behavior with the teens and tens was an open issue.

Table 5 gives the results for the first trial (lists I–IV). As expected, many errors occurred with the inverted items (list III). Some errors were evident in list I. We think that these latter errors can be traced back to the same erroneous strategy as in list III, that is, if AT is ready to positively match “vierundsechzig” (64; literally: four-and-sixty) with 46, then he will also tend to reject identical pairs of verbal numerals and Arabic numbers. The teens and tens in the identical list II were no problem for AT. Thus, he did not seem to apply a left-to-right strategy with the teens and tens. Instead, these items seemed to be treated as elementary (non-composed) verbal units. Finally, two errors occurred in the last list. Both concerned the inverted items (e.g., einundvierzig (41; literally: one-and-forty) → 14).

Two weeks later the experiment was repeated (see Table 5; second trial). This time AT was required to tick all nonmatching pairs. As a further modification all inverted Arabic numbers of condition IV (n = 7) were replaced by other numbers which had one digit in common with the auditory numeral (e.g., einundachtzig (81; eight-one) → 91). The results (see Table 5, second trial) now demonstrate close to perfect performance in all lists except for the inverted items.

phemes of these German number words are not linked by “und” (and) in contrast to greater compound numbers (e.g., 23 = dreundzwanzig (literally: three-and-twenty)).
<table>
<thead>
<tr>
<th></th>
<th>First trial</th>
<th>Second trial</th>
</tr>
</thead>
<tbody>
<tr>
<td>List I: Matching stimuli (no teens and tens)</td>
<td>16/20</td>
<td>19/20</td>
</tr>
<tr>
<td>List II: Matching stimuli (teens and tens only)</td>
<td>20/20</td>
<td>20/20</td>
</tr>
<tr>
<td>List III: Nonmatching stimuli (no teens and tens)</td>
<td>4/20</td>
<td>7/20</td>
</tr>
<tr>
<td>List IV: Nonmatching stimuli (including teens and tens)</td>
<td>18/20</td>
<td>20/20</td>
</tr>
</tbody>
</table>

The results of the second trial underline that AT was suffering from a rather specific impairment in matching items whose names have to be composed by more elementary number names. There were no major difficulties in processing teens and tens which were obviously treated as noncomposed lexical units by AT. The results obtained in the matching tasks are thus concordant with the results in reading aloud reported above.

**Semantic Comprehension of Arabic Numbers**

It was of crucial importance to find out whether AT’s difficulties in reading aloud Arabic numbers and in matching heard numbers to seen Arabic numbers extended to pure visual number comprehension tasks as well, that is, to tasks which did not demand any transformation into a verbal number code. Therefore, we confronted him with the following comprehension tasks for Arabic numbers.

**Number comparison.** AT was shown cards with two numbers on each of them. The patient was required to compare the magnitude of the two numbers and to tick the bigger one. Twenty pairs of ones and teens were presented. Half of the pairs was composed of elements of different classes (e.g., 5 and 17) and half of items of the same classes (e.g., 15 and 12). AT’s performance was flawless.

**Arranging of number triplets.** AT was presented with 12 number triplets. Each triplet consisted of 3 numbers depicted on separate movable tokens. It was AT’s task to change the wrong sequence of numbers into the right sequence according to their ascending magnitude. The triplets consisted of 2 one-digit, 4 two-digit, 3 three-digit, and 3 four-digit numbers and were presented in random order. AT performed perfectly.

**Arranging of number triplets (including inverted items).** This time 18 triplets of two-digit numbers were presented (same task as above). Two items consisted of the same digits in different order (e.g., 43, 34). Half of these pairs started with the smaller number. A third item was chosen from the interval in-between (e.g., 37). The position of this last item was balanced (in front of, behind, between the two others). The order of presentation was randomized. AT performed fast and accurately.

In all three tests AT did not produce a single error. He performed very fast and did not express any uncertainties in his decisions. In particular, there was no shred of evidence for the assumption that the symptom of inversion errors shown in reading aloud and in matching tasks was part of his visual input processes or his semantic processing of figures.
The outstanding feature of AT’s errors in reading complex Arabic numbers was his tendency to produce responses that corresponded to the reversed order of the target digits. Given the target, e.g., 83 he read ‘‘achtunddreißig’’ (thirty-eight) exchanging not only the involved digit identities but also their place information, that is, the wrong figures were correctly accommodated to their new places (e.g., from the ones to the tens and vice versa). This error type exclusively occurred with numbers where the rule of inversion had to be applied. This is the case in most two-digit numbers standing on their own or as final elements of more complex digit strings (excluding tens and numbers with the digit ‘‘0’’ in prefinal position; in addition, please note that in double digit numbers reversals are virtually undetectable (e.g., 22, . . . , 99)).

Inversion errors did not only occur in reading aloud but also in tasks that required AT to match a heard number word to a seen Arabic numeral. Like in reading aloud the basic conflict between the visual and the phonological order of the digit string was preprogrammed. Unlike in reading aloud where one goes from the visual input to the linguistic form, in matching tasks the auditory phonological information is presented simultaneously with the visual choices. AT’s strategy in the matching tasks was clearly phonologically based: He repeated the heard number word and segmented it into its constituting morphemes. Then, moving from left to right he compared the morpheme string with the digit string on an element-by-element basis thus ignoring in many cases the rule of inversion.

Turning to the input side of AT’s number reading abilities there was no indication of disturbed access to the magnitude or ‘‘meaning’’ of the visually presented one- to four-digit numbers. AT’s visual input and his semantic processing as tested by number comparison and number arranging proved to be intact. Even in tasks specifically designed to induce inversion errors AT performed flawlessly. The absence of inversion errors in visual number comprehension is not unexpected. In contrast to reading aloud visual Arabic number comprehension is based on a strict left-to-right parsing. Problems with the inversion rule should not interfere with visual comprehension of Arabic numbers. Thus, AT’s problems with inversion items cannot be located at the visual input component or semantic component of Arabic number processing. AT differs therefore from the case NR (described by Noel & Seron, 1993), a demented patient with relatively specific deficits in the Arabic comprehension system.

Visual deficits in parsing digit strings can also be excluded as the responsible impairment underlying AT’s number reading problems for the following reasons. First, of course, visual deficits should have affected his number comprehension abilities. This was not the case as just stated. Second, it is a prerequisite of inversion errors that both involved digits must have been
recognized correctly. Third, in some of the approximation sequences AT was
able to name aloud both single elements of a two-digit number but notethe-
less failed to read aloud the whole numeral. Finally, he never made inversion
errors with teens (e.g., 19 → einundneunzig (ninety-one)) in reading aloud
and in the yes/no matching task. In the multiple choice matching task only
two inversion errors occurred in which teens were involved, both with three-
digit items. Moreover, the fact that there were no inversion errors with the
teens in reading aloud confirms the assumption that teens (also in German)
may be represented as elementary (noncompositional) lexical units (see Mc-
Closkey & Caramazza, 1987, for the lexical classes of spoken numbers in
English; see Deloche & Seron, 1982, 1987, for the French system). Taken
together, we think that—on the basis of AT’s pattern of behavior—a visual
hypothesis, namely, that AT’s inversion errors are due to impaired perceptual
analysis of the digits, can be ruled out.

A more plausible account about the locus of AT’s specific symptom in
number processing would be that AT’s inversion errors arise due to damage
to the output system for verbal numbers. This account would be consistent
with the observed lack of inversion errors in visual and semantic tasks which
did not demand any phonological mediation. According to this hypothesis,
AT’s inversion errors could be traced back to morphological errors in com-
posing sequences of phonological number words, that is, the involved mor-
phological constituents would be arranged in the wrong order by a mor-
phonological output system.

Under this hypothesis AT’s inversion errors could be accounted for by a
postsemantic deficit involving morphological (or as McCloskey prefers to
say—syntactic) operations within the phonological numeral production com-
ponent (see the McCloskey model; Fig. 1). Similarly, morphological disor-
ders within the “verbal word frame” component of the Dehaene model could
trigger misorderings of activated number forms of the type seen in AT (see
Fig. 2).

However, this morphological output hypothesis raises several problems.
Let us discuss some of them within the single (semantic) route model of
McCloskey. First, the hypothesis clearly predicts morphological output er-
rors regardless of the modality of input (auditory, visual, semantic) and not
only in tasks where the incongruency of the visual–arabic and the phonologi-
cal order of the numerals comes into play. In a semantically induced task
in which AT had to first rate the age of depicted human faces internally and
then to verbally express his estimate, no evidence (with one ambiguous case)
for inversion errors could be found. Moreover, inversion errors were encoun-
tered neither in AT’s spontaneous speech output (though not formally stud-
ied—nostra culpa) nor in reading aloud verbal numerals (though his perfor-
ance here was too severely compromised to allow firm conclusions).
Inversion errors were also absent in number repetition where morphophono-
logical processing of the numerals could also be assumed. Finally, speaking clearly against the morphological output hypothesis, errors of inversion were found in matching tasks where his morphophonological output was correct. Here, he heard the number word (e.g., vierundsechzig; 64; literally: four-and-sixty), he repeated it correctly and then matched it wrongly with the inverse order of figures (here 46). This behavior is not consistent with the morphological output hypothesis because this hypothesis predicts that as soon as the spoken output is correct no matching errors with the visually presented Arabic numbers should occur.

There are even more problems and open issues with the morphological output hypothesis. Interestingly, McCloskey (1992, see footnote 3) as well as Dehaene and Cohen (1995, see footnote 1) acknowledge that the mechanisms of verbal numeral production cannot fully be separated from more general language mechanisms outside the number domain. Thus, in both models it is unclear whether there is a morphological mechanism specifically devoted to number words or not; if this is not the case, morphological errors in tasks other than number processing are also to be expected in AT. We did not observe any inversion errors in morphologically complex words (inflected, derived, compound) in AT’s spontaneous speech nor did we find inversion errors in the compound noun naming test (see above, Background Investigations).

If we assume that there are shared components in morphological processing of number words and other words (or that there are at least analogies between them in the way of how morphologically complex items are accessed), it is unclear how inversion errors could arise using the semantic reading route in the McCloskey model. Let us assume that the abstract semantic representation of the target is appropriately specified (in McCloskey’s notation each basic quantity is represented (in brackets) together with its associated power of 10 (noted as 10EXPn); e.g., the abstract representation of 26 is (2) EXP1; (6) EXP0). This semantic representation has to be mapped onto the level of lexical sound forms (here “sechsundzwanzig”). Most current psycholinguistic models covering polymorphemic word access stress the role of whole-word address procedures. Only if this route of whole-word

2 Obviously, words (and nonwords) can be repeated bypassing semantic representations (see for aphasiological evidence, e.g., Caplan, 1992). Accordingly, we assume that also number words can be repeated by a nonsemantic route (though this possibility is not explicitly incorporated into the McCloskey model). Nevertheless, we think that our argument about missing inversion errors in repetition is not trivial since the potential sensitivity of the repetition task for morphological (number unspecific) parameters was shown by case studies (e.g., Miceli & Caramazza, 1988; Katz & Goodglass, 1990).

3 Indeed, it has been suggested that polymorphic words are lexically stored as whole units (see Butterworth, 1983; see also Stemberger & MacWhinney, 1986, who postulate whole-word representations for high-frequency regularly and all irregularly inflected forms). Others argued for morphologically decomposed forms of lexical representation (see, e.g., Caramazza,
activation fails or works too slowly morpheme-based access and composition procedures are engaged (see the morpheme address procedure in the Augmented Addressed Morphology model of Caramazza et al., 1985, 1988; see also Semenza, Butterworth, Panzeri & Ferreri, 1990). Obviously, with a whole-word routine no morphological errors can be expected at all. So, let us assume that this routine is dysfunctional to some extent in AT and that the morpheme-based back-up procedure is activated. Thus, each component of the abstract representation is mapped onto its appropriate number morpheme, e.g., (2) EXP1 is mapped onto “zwanzig” (twenty) and (6) EXP0 is mapped onto “sechs” (six). A morphological (or syntactic) misordering of the morphemes would end up in “zwanzigsechs” but never in an inversion error as described for AT, namely, “zweiundsechzig” (62).

Given that AT’s inversion errors were restricted to tasks involving Arabic-to-verbal transformation procedures and given the difficulties to account for this error type within the semantic transcoding model of McCloskey, we conclude that his inversion errors are specific to reading Arabic numbers and that they are motivated by the conflict between the left-to-right visuospatial arrangement of Arabic figures on the one hand and the temporal sequence of (certain) German number morphemes on the other hand caused by the German rule of inversion.

For models of number processing this account has interesting implications. As stated in the Introduction, models of number processing differ with respect to the format of representation that connects Arabic number input systems and verbal number output systems. While some authors assume an exclusively semantic mediation between input and output components (see the model of McCloskey et al.; Fig. 1), others argue in favor of the existence of asemantic mechanisms which subserve input/output connections (see, e.g., Deloche & Seron, 1987; Dehaene & Cohen, 1995; see Fig. 2).

We think that AT’s inversion errors cannot be predicted by the single-route model of McCloskey and that the case of AT can provide evidence against the hypothesis of an exclusively semantically mediated reading process of Arabic numbers. AT’s error pattern is better captured by the approach of Cohen & Dehaene (1991) who state “that the workbench storing the input data for number reading is visual rather than semantic in nature”. Their proposal for a nonsemantic number reading process which is based on visual input is as follows: First, number length is determined based on a first visual analysis; then, a standard syntactic frame is activated (e.g., TENS:_ONES:_ for 71 or 17) which is further specified as a word frame which addresses the correct lexical classes of the verbal numeral (e.g., TEENS:_ for

---

Miceli, Silveri, & Laudanna, 1985; Caramazza, Laudanna, & Romani, 1988). However, their model assumes a whole-word access procedure for known words and a morpheme address procedure only for novel words. Both access systems work in parallel; the former being faster than the latter.
We think that these operations were largely unaffected in AT’s inversion errors. They were correctly built up with respect to the frames into which the digits had to be integrated. Moreover, AT was very successful in reading teens that were retrieved as elementary items (or lexical wholes) and that were not involved in his reversal errors. However, according to Cohen & Dehaene, after a word frame has been established a second visual analysis is necessary in which the digit identities are retrieved from the verbal number lexicon. We propose that this process of filling the slots of the defined word frame by phonological number forms was impaired in AT. Instead of beginning the filling operation with the last digit he began with the left-most digit, successively integrating the seen digits into the correct word frame ending up in inversion errors which did not correspond with the semantic value of the digit string.

Cohen et al. (1994) have reported on a patient with ‘‘deep’’ reading symptoms that extended to Arabic numbers (see Introduction). The authors questioned the possibility to find any ‘‘surface’’ reading symptoms for Arabic numerals because of the regular character of the Arabic reading system (with only few exceptions in French). We think that the inversion rule of the German Arabic reading system provides a possibility to study errors resembling ‘‘surface’’ errors or ‘‘over-regularization’’ errors in reading words (though not on a segmental but rather morphological level) and that errors with this type of ‘‘irregular’’ targets support the hypothesis that reading can be accomplished other than only by a semantic route.

REFERENCES

Blanken, G. In preparation. The production of nominal compounds in aphasia.


