Are Number Words Fundamentally Different? A Qualitative Analysis of Aphasic Errors in Word and Number Word Production

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Abstract: A number of previous studies reported dissociations between the processing of number words and other words and reasoned that there are fundamentally different mental representations and/or processing strategies related to these types of words. Messina *et al*. reported the performance of Italian aphasic patients with words and number words in different tasks [1]. In line with previous studies, they found that lexical errors formed the dominant error type in number words, whereas phonological errors were the most frequent error type in other words. Messina *et al*. [1] concluded that speech production processes differ categorically between number words and other words, leading to qualitatively different error patterns in language breakdown. The present study examined error types in number words and other words in a sample of 15 German patients with aphasia using the same tasks as Messina *et al.* [1]. Performance in reading and repeating number words and other words was analysed. In general, we replicated the dissociation of error types between number words and other words reported by Messina *et al*. [1] and others. However, in contrast to previous assumptions this dissociation was not categorical but rather gradual. We suggest that psycholinguistic stimulus properties (such as number of repetitions per morpheme) and type of task influenced error types in a gradual fashion.

Keywords: Aphasia, number word processing, transcoding, phonological errors, lexical errors, dissociation.

1. INTRODUCTION

1.1. Dissociation between Number Words and other Words in Clinical Cases

During the last two decades, the processing of number words[1] attracted increasing attention. A number of researchers reported (double) dissociations between the processing of number words and other words[2] in aphasic and/or acalculic patients. For instance, Anderson *et al*. described a non-aphasic patient who showed impaired reading and writing of letters and words, while performance turned out to be unaffected for Arabic numbers [2] (see also [3] for a similar pattern of performance).

With respect to semantic representations, Cipolotti *et al*. reported an acalculic patient (CG), who showed a selective deficit in semantic knowledge related to numbers [4]. CG was completely unable to deal with numbers larger than four in any modality. This severe impairment was not paralleled in non-number words. Therefore Cipolotti *et al*. suggested that there are separate semantic systems for number-related knowledge and for knowledge related to other concepts [4]. According to this interpretation, CG's symptoms resulted from an impaired semantic system for numerical knowledge. Similarly, Delazer *et al*. described patients suffering from posterior cortical atrophy who showed severe deficits in numerical semantic knowledge but intact non-numerical semantics [5]. In contrast, Butterworth, Cappelletti and colleagues [6-8] reported a patient (IH) suffering from semantic dementia, who showed selectively impaired performance for words and non-words. Although reading and writing words was virtually impossible for him, he was still able to read almost all number words correctly [6-8]. In the light of this pattern of performance the authors assumed that semantic knowledge may be selectively spared for numerical content [6-8] (see also Zamarian [9] for a similar case of spared numerical

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[1]In the following, the term "number words" will be used for written and spoken numerals. The term "numbers" will be used in a broader sense denoting number words as well as Arabic numerals.
[2]The terms "other words" or "words" will be used to denote existing non-number words.

E-ISSN: 2311-1917/13

semantics with severely impaired non-numerical semantic knowledge).

With respect to post-semantic processing, Denes and Signorini reported on an acalculicpatient, who displayed a specific deficit in reading Arabic numbers and written number words [10]. He also made errors in reading single letters and non-words despite unimpaired reading of other words. Denes and Signorini reasoned that number words "… are likely to be processed similarly to non-words through a non-semantic transcoding mechanism" (p. 275) [10].

Deficits at the level of lexical and/or sublexical processing have also been reported to dissociate between number words and other words. Bachoud-Lévi and Dupoux described an aphasic patient (DPI), who showed intact number word production but partially impaired production of other words [11]. DPI was able to name numbers correctly, but he failed to name objects. In trying, he almost consistently produced phonological paraphasias. Furthermore, concrete nouns and verbs were more difficult for him than abstract words. This pattern of results was ascribed to a deficit at the level of phonological word-form retrieval [11]. Moreover, Bachoud-Lévi and Dupoux suggested that the organisation of word form storage may be influenced by semantic variables (e.g. numerical vs. non-numerical concepts) [11]. Marangolo *et al*. reported on an aphasic patient (FA), who failed selectively in spoken production of complex Arabic numerals and written number words [12]. However, his semantic knowledge about numbers was intact just as his production of written number words and Arabic numbers. Reading aloud other words, non-words, syntagmas, and sentences was largely fine. Therefore this patient showed selectively impaired spoken number name production, lexical errors forming the most frequent error type. Interestingly, in verbal production of non-number words he infrequently produced phonological errors [12]. Marangolo *et al*. assumed "…a categorical organisation in the lexical-semantic system." (p. 997) [12]. More specifically, the authors hypothesised different processing mechanisms for the selection of words and number words at the lexical/phonological level [12]. In another study Marangolo *et al*. examined an aphasic patient who showed impaired spoken number word production, unimpaired written number production, and flawless semantic knowledge of numbers [13]. They concluded that dissociations between the production of number words and other words may not only be caused by a categorically organised semantic system but also by separate lexical mechanisms [13]. In addition they suggested different modality-specific output lexicons for the written and spoken production of numerals [13]. Highlighting the connections between semantic and lexical knowledge, Domahs *et al*. reported on a patient with primary progressive aphasia (HT) [14]. This patient showed a pronounced dissociation between number words and other words in all four modalities (auditory and visual lexical decision, naming, reading aloud, writing to dictation). Her number word processing was flawless in all modalities in contrast to her processing of other words. Crucially, her semantic knowledge was argued to be largely unimpaired for both kinds of words. In the light of their own findings and cases reported in the literature, Domahs *et al*. suggested that number words and other words may be differentially organised at the semantic level of processing and the lexico-semantic connections, both functionally and neuro-anatomically [14].

With respect to post-lexical processing, Cohen *et al*. examined the ability of reading aloud written number words, Arabic numbers, and other words in a patient with Wernicke's aphasia [15]. The results showed a double dissociation between number words and other words: In the production of words phonological errors were the most frequent error type, whereas in number words the most frequent error type were lexical errors. Cohen *et al*. found no evidence for an influence of lexical variables like frequency, imageability, and grammatical class in number word production. Therefore, the authors concluded that their patient showed a deficit in post-lexical phoneme activation. More specifically, they suggested that number words are processed on the basis of different units compared to words: "While phonemes are the building blocks of most words, one may say that … individual number words [are] the building blocks of complex numerals" (p. 1058) [15]. Consequently, phonological errors in word production will arise because of incorrect phoneme-retrieval, while lexical errors in number word production will arise because of incorrect morpheme-retrieval.

Dotan and Friedmann described six aphasic patients with a deficit at the level of the phonological output buffer [16]. These patients exhibited what the authors called the "STEPS phenomenon" (Stimulus Type Effect on Phonological and Semantic errors): They all predominantly made phonological paraphasias on words and semantic[3] paraphasias on number words. In line with previous studies, Dotan and Friedmann concluded that number words and other words are processed differently, arguing that "…the basic phonological building blocks of ordinary words are phonemes, but the building blocks of numbers … are whole words (digits)" (p. 83) [16]. Building blocks may be mis-selected but as they are assumed to be "atomic" they may rarely be broken. Interestingly, however, Dotan and Friedmann discovered that the semantic errors dominated not only in number word production, but also in the production of function words, letter names, and morphological affixes. Moreover, descriptive statistics reported by Dotan and Friedmann seems to suggest different degrees of skewness in the distribution of semantic and phonological errors across different tasks (reading, naming, or repetition) and across different patients. Unfortunately, this variation remained unexplained.

Semenza *et al*. [17] and Bencini *et al*. [18] reported on an Italian aphasic patient (GBC) with a phonological output deficit for words sparing number words. Interestingly, GBC's vowels were more affected from substitution errors than consonants. In number word production no phonological but only few lexical substitutions were observed [17, 18]. Semenza *et al*. suggest that number words can be produced *via* dedicated numerical (orthographic or Arabic)-to-spoken name transcoding algorithms that need not contain semantic information. Crucially, they predicted "that all patients with phonological deficits at the word activation level would be relatively less impaired when producing number words than other words" (p.429) [17]. Bencini *et al*. localized GBCs deficit functionally as a deficit in word form encoding for number words. They suggested the existence of separate representations in the production of number words and other words. Bencini *et al*. concluded that "…number words do not require the additional CV-tier…" during phonological processing at the lexeme level (p.1055) [18]. Therefore these two word categories may differ at the level of phonological encoding in production prior to articulation. Based on their careful control of psycholinguistic stimulus properties, Bencini *et al*. could demonstrate that the dissociation of error types between words and number words was not due to variables like grammatical class (proportion of phonological errors did not differ significantly between nouns, verbs, adjectives, and function words), frequency of occurrence, or word length (number of syllables or characters) [18]. Thus in contrast to findings reported by Dotan and Friedmann [16], function words patterned together with words and not with number words.

Recently, Messina *et al*. reported the performance of 57 Italian aphasic patients in repetition, reading aloud, and writing to dictation of number words and other words [1]. They found that repetition and reading aloud of number words predominantly led to lexical errors (95% and 93%, respectively) while phonological errors dominated for other words (99% in repetition and 93% in reading). Phonological/orthographic errors also dominated in writing to dictation of words (98%) while there was no such clear-cut error distribution for writing to dictation of number words (39% lexical and 61% phonological errors). Messina *et al*. concluded that mental representation and/or processing of number words and other words are organised in a principally different way. Specifically, they argued for differential processing routines at the lexical and phonological/orthographic level for number words and other words. Following Cohen *et al*. [15] they suggested that the basic processing units may be phonemes in the case of words but morphemes in the case of number words. Thus, this account could be termed *categorical* as it assumes processing to depend on word type in a categorical way. With respect to lexical errors in number words Messina add that "… this specific error pattern could be seen as a consequence of a deficit of the 'semantic route' in processing number words, analogous to the semantic errors in word processing made by deep dyslexic patients […] or to an access deficit to the phonological lexicon" (p. 492) [1].

1.2. Models of Word and Number Word Processing

Numerous models have been developed to describe the processing of words (e.g. [19, 20]) and number words (e.g. [21, 22]). However, to our knowledge only one model has explicitly tried to describe the processing of words and number words simultaneously – WEAVER++ [23]. Basically, WEAVER++ is a computational implementation of the most relevant aspects of the lemma model ([19]) and the network model proposed by Dell [20]. It is able to successfully simulate the naming performance of healthy persons

[3]Note that the same type of errors (e.g., "seven" instead of "three") which Dotan classify as "semantic" hast been classified as "lexical" by all previous studies [16]. Superficially, these errors could be both, semantic or lexical. However, neither patients reported in previous studies nor patients reported by Dotan seemed to have semantic deficits [16]. Therefore we will use the term "lexical" throughout the rest of the paper.

and aphasic patients for pictures/words and digits/number words.

Naming in WEAVER++ consists of four processing steps: *conceptual identification*, *lemma retrieval*, *word-form encoding,* and *articulation*. Lemma retrieval and word-form encoding are conceived as discrete processes such that only one form of a selected lemma becomes activated and encoded after conceptual identification. Arabic numbers and number words activate lemmas and their output form in parallel. According to WEAVER++, word and number word production proceeds as follows: At the level of morphological encoding morphological features (e.g. grammatical number) will be defined. Afterwards, segments as well as a word's metrical structure (number of syllables and stress pattern) will be selected at the level of phonological encoding. Finally, segments will be assigned to their respective syllable positions at the level of phonetic encoding.

Roelofs argued that numbers are named more like words than like pictures [23]. Crucially, the model seems to predict that both lexical errors (at the level of lemma-retrieval) and phonological errors (at the level of phonological encoding) can occur during the verbal production of both words and number words.

1.3. The Present Study

In sum, a number of clinical case studies have demonstrated dissociations between the processing of number words and other words. One relevant type of observation concerned the kind of errors produced for both types of words: Number words predominantly led to lexical errors whereas other words predominantly let to phonological errors [1, 12, 15-18]. This pattern of performance has been explained by a 'categorical' account assuming fundamentally different processing units for both types of words at the lexical and/or post-lexical level: While the processing unit may be phonemes in the case of words, it may be morphemes in the case of number words [1, 15]. Unfortunately, the categorical account has remained underspecified, failing to explain how exactly processing of both types of words can be perceived. On the other hand, the only existing explicit psycholinguistic model which tries to grasp processing of both number words and other words [23] does not assume fundamentally different processing routines. In particular, it is not built on qualitatively different processing units, nor does it seem to predict qualitatively different types of errors.

In our view, the categorical account in its present state leaves open a number of questions, including the following:

1) If processing units and/or processing routines are fundamentally different, how can the occurrence of some – although few – deviating errors be explained? Thus, if morphemes were the processing unit of number words, how to explain 7% phonological errors in reading aloud of number words as observed by Messina [1]? Such deviant errors have been reported repeatedly [15, 16]. This conceptual question turns into a methodological one if one asks which distribution of errors can be regarded as sufficiently skewed to assume a qualitatively different processing routine.

2) If number words are processed in a fundamentally different way – why should this be the case? Because they have a very high frequency of occurrence? Because they are morphologically complex? Because there is a ubiquitous notation (Arabic numbers) which seems to favour morpheme based processing? Are non-number words sharing the same properties (e.g. high frequent, morphologically complex words or words usually written in a logographic script like Chinese) predicted to behave like number words? In fact, Dotan and Friedmann reported that function words, letter names, and morphological affixes seemed to behave like number words [16]. On the other hand, Bencini *et al*. found no influence of grammatical class (function words patterning as other non-numerical content words), frequency, or word length as measured in syllables or characters [18].

3) If the processing units for number words are morphemes rather than phonemes – how exactly articulatory gestures are accessed from these morpheme-based units?

4) If number words and other words lead to different types of errors because of their different processing units – could the distribution of error types be modulated by task (e.g., repetition vs. reading), modality (e.g., oral vs. written), or psycholinguistic properties of the individual stimulus beyond type of word (e.g., number of morphemes, number of repetitions per task)? If so – how could such a modulation be explained?

Recall that a modulation by task and/or modality has been reported by Messina *et al*. [1], who failed to observe the same clear-cut dissociation of error types which they found in repetition and reading in writing to dictation of number words. Task dependent variation has also been observed by Dotan and Friedmann [16].

Unless these questions can be answered convincingly by the categorical account, an alternative explanation for the dissociation of error types can be adopted. Rather than assuming fundamentally different processing units and/or routines one could assume that both types of words are processed in basically the same way, as proposed in the WEAVER++ model [23]. Different error patterns could then be explained by the fact that number words typically differ from other words in terms of individual values of psycholinguistic variables such as frequency of occurrence or number of morphemes (for a discussion of some additional variables see Domahs *et al*. [14]). In contrast to the categorical account, however, this difference would be gradual rather than categorical, allowing for variance across items, tasks, and subjects: Variation across items may occur as psycholinguistic properties do not only vary between but also within word types. For instance, within the category of number words word frequency tends to decrease [24, 25] and number of syllables and morphemes tends to increase [25] with increasing numerical value. Number words consist of only a small set of morphemes which are repeatedly used, resulting in a high functional load, which can be measured as relatively low type/token ratio for these morphemes. However, type/token ratio is not consistently high for other morphologically complex words. Rather, there are categories like geometrical words showing the same phenomenon i.e. the same small set of morphemes used relatively often. Variation across tasks may occur as different task demands may be influenced by different psycholinguistic variables. For instance, one task may place relatively stronger emphasis on lexico-semantic processing compared to another task, the latter potentially leading to more errors of the lexical type than the former. Messina *et al*. as well as Dotan and Friedmann found numerically different results for different tasks [1, 16]. These results were compared neither directly nor statistically and they remained unexplained. Variation across subjects may occur depending on individually preferred processing strategies or individual profiles of impairment. Most papers discussed above were single case studies [2, 4, 6-8, 10-12, 14, 15]. On the other hand, group studies did not deal with single case descriptions [1, 5, 16]. Therefore possible variation across subjects could not be compared and assessed in both types of study. Note that the gradual account sketched so far does not exclude the possibility that morphemes are relatively more important in the production of number words compared to other words while the opposite may be true for phonemes. Importantly, however, this processing difference would be gradual rather than categorical and it may be influenced by more than one variable.

In the light of these considerations, we aimed to replicate the results reported by Messina *et al*. [1] and similar findings with German aphasic patients. In general, we expected to observe a similar global dissociation of error types between number words and other words: (1) Lexical errors will dominate for number words while phonological errors will dominate for other words. Addressing the different predictions of the categorical and the gradual account and based on the assumptions of WEAVER++ [23], we formulated four more specific hypotheses: (2) Beyond the global dissociation of error types, “deviant” errors do occur, i.e. phonological errors in number words and lexical errors in other words. (3) Beyond the global dissociation of error types, individual patients may show a “deviant” pattern. (4) Beyond the global dissociation of error types, the distribution of error types may be modulated by psycholinguistic stimulus properties other than word type, e.g. number of morphemes and type/token ratio. (5) Beyond the global dissociation of error types, the distribution of error types may be modulated by kind of task (e.g. repetition vs. reading).

In sum, we expect to replicate the global dissociation between number words and other words in terms of error types as described in previous studies [1, 15-18]). However, in contrast to the categorical account put forward by Cohen *et al*. [15], Messina *et al*. [1], and others, we assume this dissociation to be gradual rather than categorical in nature.

2. METHODS

2.1. Patients

For this retrospective study we inspected data sets of 37 consecutive aphasic strokepatients, who participated in a larger study on aphasia and acalculia at the RWTH Aachen University Hospital in Aachen, Germany. To be included in the present analyses, all relevant tasks had to be performed completely, patients should have committed at least six errors in number transcoding tasks[4] and be native speakers of German. Twelve patients were excluded from analyses because of incomplete test results. Another nine patients were excluded because they produced less than six errors in transcoding. Patients included in the analyses made 8 to 46 errors in number transcoding tasks (mean 22.6). One patient was excluded because he was bilingual. Hence, we included 15 patients in our analyses (four women, eleven men). The group included three Wernicke's, four Broca's, one transcortical-sensory aphasic patient, and one patient who showed only mild residual symptoms (syndromes based on the classification of the Aachen Aphasia Test (AAT [27])). In six cases no aphasic syndrome could be diagnosed reliably. Four patients showed additional alexia, dysarthria, or apraxia of speech. Age ranged from 37 to 72 years (mean 51 years) and time post onset ranged from 1 to 80 months (mean 28 months). Appendix 1 shows relevant demographic data of our patient sample.

2.2. Tasks

With respect to number processing, we evaluated the patients' performance in the transcoding tasks of the *Number Processing and Calculation Battery* (NPC; [26]): reading aloud Arabic numbers (18 items, e.g. *5*, *2499*), writing Arabic numbers to dictation (18 items, e.g. *9, 3365*), reading aloud written number words (ten items, e.g. *ACHT* (eight)), writing Arabic numbers to written number words (ten items, e.g. *ZWÖLF* (twelve)). In contrast to Messina *et al*. [1] we did not include writing number words to dictation and writing number words to Arabic numbers[5]. Items of all tasks included morphologically simple as well as complex number words. Furthermore, patients performed a specifically designed number word repetition task, consisting of twelve morphologically simple number words and twelve morphologically complex number words.

Production of words and non-words was evaluated using selected tasks from the *Aachen Aphasia Test* (AAT, [27]), a screening of reading performance for words and non-words (home-made reading screening, RWTH-Aachen, Germany), and a word and non-word-repetition task. For our study we only used the AAT subtests repetition of one-syllable words (ten items e.g. *Glas* (glass)), repetition of loan words (ten items, e.g. *Telefon* (telephone)), repetition of compound words (ten items, e.g. *Haustür* (front-door)), reading aloud (seven words, e.g. *Wahl* (vote)) and *writing to dictation* (seven words, e.g. *Künstler* (artist)).

The following item sets (all n = 10) from the reading screening were included in the analyses: short morphologically simple concrete words (three or four phonemes, e.g. *Rad* (wheel)), longer morphologically simple concrete words containing two to four syllables (e.g. *Maschine* (machine)), short morphologically simple abstract words (e.g. *Idee* (idea)), low-frequent short morphologically simple words (e.g. *Beule* (bump)), word-like pseudowords containing two to four syllables (e.g. *Reile* (like *Reibe*)) and pseudowords not resembling existing words containing two or three syllables (e.g. *Pibe*). The repetition task consisted of twelve morphologically simple (e.g. *glatt* (flat)) and twelve morphologically complex geometrical words (e.g. *sichelförmig* (sickle-shaped)).

Note that repetition was evaluated using two types of morphologically complex words: non-specific compounds from the AAT and geometrical words from the specifically designed repetition task. This latter repetition task was created to use words, which resemble number words in a potentially relevant aspect: Stimuli were morphologically complex, composed of only a few different morphemes appearing repeatedly. Thus, the complex geometrical words always included one of three different final morphemes, -*förmig* (-shaped), -*artig* (-like) and -*rund* (-round) while the complex number words repeatedly contained one of the multiplier words -*zehn* (-teen), -*hundert* (-hundred) and -*tausend* (-thousand). Table **1** indicates relevant psycholinguistic properties of words and number words used in the repetition tasks, showing that geometrical words were in some respect more similar to complex number words than other words.

Note that – due to the fact that analyses were based on different standardized tests – number transcoding tasks used in the present study included three to four times as many items as those used by Messina *et al*. [1], whereas tasks used to examine the production of other words and non-words contained significantly less items than those used by Messina *et al*. [1].

2.3. Analyses

The present analyses were performed in close analogy to those reported by Messina *et al*. [1]. We

[4]Six errors equal about 7% of all items in analogy to the criterion set by Messina *et al*. [1].
[5]The NPC does not contain these two tasks.

Table 1: Psycholinguistic Variables Characterising the Different Kinds of Stimuli

	Simplex words	Compounds	Geometrical words	Complex number words
Example	*Tisch* (table)	*Handschuhfach* (glove box)	*kreisrund* circular	*dreiundsechzig* (sixty-three)
Morphological complexity	-	+	+	+
Number of types	32	35	16	14
Type/token-ratio	1	0.92	0.62	0.37
Number of morphemes	1	1 – 6 (3.8)	2 – 3 (2.2)	2 – 4 (3.2)
Word-length	1.7	4.9	3.6	3.6

Number of types as well as type/token-ratio are indicated for the occurrence of morphemes in the tasks used. Number of morphemes is indicated as range and mean. Word length is indicated as mean number of syllables. Words for geometrical shapes were only used in repetition.

used the same error categories just adding the category *non classifiable*. Thus, for number words and Arabic numbers we used six different categories: lexical errors (e.g. *38* instead of *57*, *108* instead of *118*), illegal numbers (e.g. **einhundertzweihundert* (one hundred two hundred), isolated listing of each digit (e.g. (*)*eins null vier* (one zero four)), phonological/ orthographical errors (at least two substitutions, e.g. **fülf* instead of *zwölf* (twelve)), mixed errors (combined phonological/orthographical and lexical errors, e.g. **schünf* instead of *vier*(four) resembling *fünf* (five)), omissions, and non–classifiable responses/errors (e.g. *einsrunter von 2500* (one below 2500) instead of *2499*). For words we used five categories: lexical errors (e.g. *Wind* (wind) instead of *Tanne* (fir)), phonological/ orthographical errors (at least two substitutions, e.g. **Hepilitis* instead of *Hepatitis*), formal/morphological errors (formal: a word response phonologically related to the target, e.g. *Wind* instead of *Kind*, *Farbgerä-teverkauf* instead of *Farbfernsehgeräteverkauf*; morphological: a word response morphologically related to the target, e.g. *Kind* (child) instead of *Kinder* (children)), omissions, and non-classifiable errors (e.g. spelling of the item, producing only one fragment of the target). Following this qualitative classification of errors, we calculated proportions of error types 'lexical' and 'phonological/orthographical' per task, word type, and patient. For both, number words and other words, lexical errors were defined as existing word other than the target and phonological errors were defined as responses which are phonologically related to the target but deviating from it by at least two phonemes.

3. RESULTS

3.1. General Results

Overall, patients made between 10% and 59% errors, depending on task and stimulus type (see Table **2**).

3.2. Error Types

We determined the proportions of lexical and phonological errors per stimulus type and task analogous to Messina *et al*. [1] (see Methods section). For both number words and other words we found a skewed distribution of error types in all tasks (see Table **3**), generally replicating the findings of Messina *et al*. [1]. However, for some tasks (e.g. repetition of number words or reading of other words) skewness

Table 2: Overall Error Rates Across Patients as a Function of Task and Stimulus Type

	Repetition	Reading aloud	Writing to dictation
Number words	36/360 (10.0%)	43/150 (28.7%)	
Words	75/480 (15.6%)	154/705 (21.8%)	57/105 (54.3%)
Arabic numbers		111/270 (41.1%)	116/270 (43.0%)
Non-words		177/300 (59.0%)	

Table 3: Proportion of Lexical and Phonological Errors in Percent Across Patients as a Function of Task and Stimulus Type

	Number words	Words	Arabic numbers	Non-words
Repetition proportion lex/phon Messina *et al*. [1]	n = 24 72/28 (95/5)	n = 32 2/98 (1/99)		
Reading aloud proportion lex/phon Messina *et al*. [1]	n = 10 96/4 (93/7)	n = 47 20/80 (7/93)	n = 18 92/8	n = 20 3/97
Writing to dictation proportion lex/phon Messina *et al*. [1]	(39/61)	n = 7 8/92 (2/98)		

Proportions reported by Messina *et al*. [1] are indicated in brackets if available. n = number of stimuli in our study.

seemed less pronounced than expected based on a categorical account. Nevertheless, in most of the tasks two-sided Wilcoxon signed-ranks tests comparing the number of lexical and phonological errors revealed significant differences in the expected direction, i.e. significantly more lexical than phonological errors in reading number words (p = .001) and significantly more phonological than lexical errors in word repetition (p< .001), word reading (p = .005), and word writing (p<.001). For repetition of number words, the Wilcoxon signed-ranks test did not show a significant difference between error types.

Appendix 2 provides an overview of the number of lexical and phonological errors per patient and task.

3.3. Single Case Analyses

In addition to the analyses of error type proportions at the group level, we also analysed single case data.The proportions of lexical and phonological errors for each individual patient are listed in Table **4** (repetition of number words) and Table **5** (reading aloud other words). Binomial tests were performed to test a weak and a strong hypothesis: The weak hypothesis assumes that both types of errors should not occur equally likely. Both the categorical and the gradual account would predict significant deviations from a balanced distribution. In line with the categorical account, the strong hypothesis assumes that only lexical errors should occur with number words whereas only phonological errors should occur with other words. The gradual account would allow for deviations from this strong hypothesis. Thus, corroboration of the weak hypothesis would be in line both with the categorical and the gradual account while significant deviations from the strong hypothesis seem compatible with the gradual but inconsistent with the categorical account.

With respect to number word repetition, binomial tests revealed that seven patients showed no significant deviation from the strong hypothesis. However, only one of these patients also produced significantly more lexical than phonological errors and can thus be regarded as clearly consistent with the categorical account. Six patients did not produce any error in this task. At least one patient (Pat. 6) showed an error type distribution which significantly deviated from the strong prediction of the categorical account (see Table **4**). Except for this one patient with a significantly deviant pattern, for number word repetition only one phonological error was produced, in line with both accounts.

With respect to number word reading, eleven patients showed numerical differences in the expected direction. However, no single patient produced enough lexical errors (max = 4) to deviate significantly from an equal probability of both error types either, i.e. there was no significant confirmation of the weak hypothesis.

In reading aloud words, five patients produced significantly more phonological than lexical errors (see Table **5**). Three of them did not deviate significantly from the strong hypothesis, thus supporting the categorical account. Three patients did not produce any error in this task. Crucially, six patients produced more lexical errors than expected by the strong hypothesis, thus providing evidence against the strict categorical account stating that lexical errors should not occur at all.

With respect to repetition of words, only one lexical error was produced at all. Two patients produced no single error in this task. However, twelve patients did not deviate significantly from the strong hypothesis and five of them produced significantly more phonological

Table 4: Individual Error Rates in Repetition of Number Words

Patient ID	Lexical errors	Phonological errors	p-value (weak hypothesis)	p-value (strong hypothesis)
6	0	6	.0321*	< .001*
3	0	1	1.00	.001*
7	0	0		
10	0	0		
17	0	0		
25	0	0		
39	0	0		
40	0	0		
8	1	0	1.00	.999**
14	1	0	1.00	.999**
26	1	0	1.00	.999**
37	1	0	1.00	.999**
15	4	0	.125	.996**
36	4	0	.125	.996**
21	6	0	.0312	.994**
total	18	7		

Indicated are two-sided p-values (for the weak hypothesis) and one-sided p-values (for the strong hypothesis) from a binomial test. The weak hypothesis states that both types of errors should not occur equally likely, while the strong hypothesis (consistent with the categorical account) states that only lexical errors should occur. Cases which deviate significantly from the hypotheses are marked with one *, while cases which show a significant bias of error type distribution confirming the hypothesis are markes with two**.

Table 5: Individual Error Rates in Reading Aloud Non-Number Words

Patient ID	Lexical errors	Phonological errors	p-value (weak hypothesis)	p-value (strong hypothesis)
26	3	14	.013	< .001*
15	6	19	.015	< .001*
21	5	6	.999	< .001*
17	7	6	1.00	< .001*
7	1	1	1.00	.001*
14	1	2	1.00	.003*
25	0	0		
36	0	0		
40	0	0		
8	0	1	1.00	.999**
10	0	2	.500	.998**
39	0	4	.125	.996**
37	0	7	.016	.993**
3	0	11	.001	.989**
6	0	18	< .001	.982**
total	23	91		

Indicated are two-sided p-values (for the weak hypothesis) and one-sided p-values (for the strong hypothesis) from a binomial test. The weak hypothesis states that both types of errors should not occur equally likely, while the strong hypothesis (consistent with the categorical account) states that only phonological errors should occur. Cases which deviate significantly from the hypotheses are marked with one *, while cases which show a significant bias of error type distribution confirmingthe hypothesis are marked with two **.

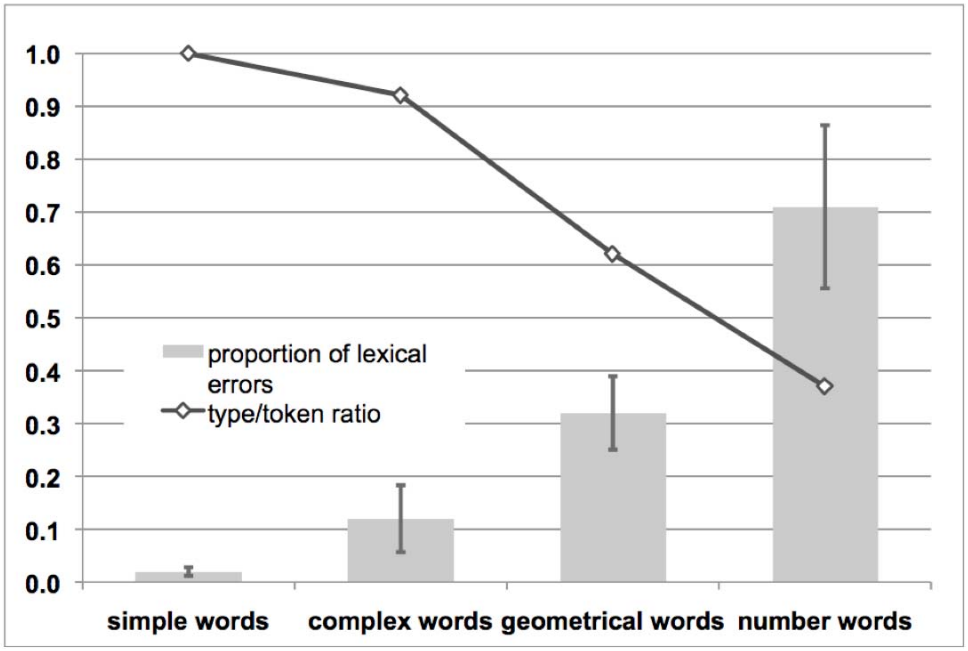

Figure 1: Type/token ratio and proportion of lexical errors in repetition for different types of stimuli.
Error bars indicate ±1 SD. Note that both geometrical words and number words were morphologically complex.

than lexical errors, consistent with the categorical (but not inconsistent with the gradual) account.

In writing words to dictation, ten patients did not deviate significantly from the strong hypothesis. Two of them also produced significantly more phonological than lexical errors. One patient did not produce any error in this task. Four patients produced lexical errors, significantly deviating from the strong hypothesis. However, none of them produced significantly more lexical than phonological errors. In fact, all four patients produced only one lexical error each.

In sum, most of the patients showed error type distributions which are consistent with the categorical account and with the group results or produced too few errors to be informative. However, in contrast to the strong hypothesis 10/15 patients produced at least one "unexpected" error in at least one of the tasks. Three of them produced phonological errors with number words and Arabic numerals in all of the tasks. One patient (Pat. 6) produced six phonological but no lexical errors in number word repetition, significantly deviating both from the strong and from the weak hypothesis and thus providing clear evidence against the categorical account. Examples of "unexpected" errors are given in Appendix 3 and Appendix 4.

3.4. Influence of Stimulus Properties

In order to examine the potential influence of selected psycholinguistic variables on the error type distribution, we analysed the proportion of lexical and phonological errors as a function of stimulus type. To this end, we focussed on the repetition[6] results of four types of stimuli (morphologically simple words, non-specific morphologically complex words, morphologically complex geometrical words, and morphologically complex number words; see Table **1**). One relevant variable characterising processing demands for these types of stimuli is their functional load as measured by the type/token ratio. Some target items consisted of only one morpheme, which is typically not repeated within the test. However, some other stimulus types consisted of several morphemes which may be repeated during testing, reflected by a relatively low type/token ratio. This is particularly true for geometrical words and number words. Using the same morphemes repeatedly during testing (and in everyday life)[7] may increase the probability that they get confused (leading to lexical substitutions) or unintendedly repeated (leading to perseverations).

In fact, inspection of the data suggested that the proportion of lexical errors increased as a function of decreasing type-token ratio (see Figure **1**). We performed repeated measures ANOVA using the

[6]As complex geometrical words were only examined in repetition, such analysis could only be performed for this task.
[7]Strictly spoken, we only measured type/token-ratios in the actual test context. However, we would like to suggest that these values may also reflect language use beyond this specific context.

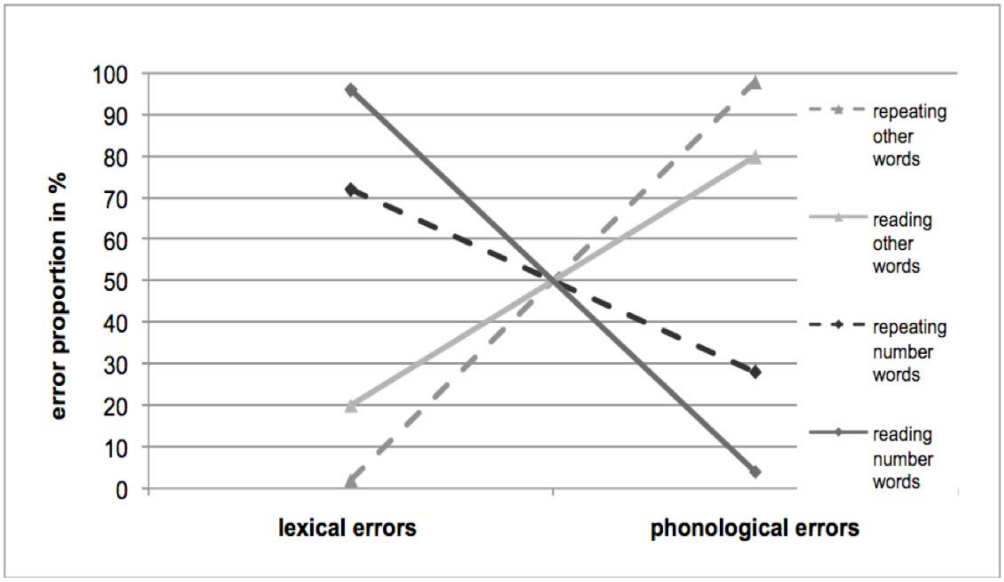

Figure 2: Proportion of lexical and phonological errors as a function of task.

proportion of lexical errors as dependent variable and stimulus type as independent variable. The analysis revealed a strong significant effect of stimulus type ($F_{(3,27)} = 6.815$; $p = .001$; partial eta² = .431). Pairwise Bonferroni-corrected post-hoc comparisons of the four stimulus types showed significant differences between simple words and number words ($p = .046$) and between non-specific complex words and number words ($p = .048$), while geometrical words did not differ significantly from non-specific complex words, complex number words or simple words.

Qualitatively, lexical errors were similar in all three classes of complex words (numerical as well as non-numerical). They consisted either of substitutions of all morphemes or of substitutions/omissions of single morphemes. In geometrical words and complex number words substitutions and omissions of the second morpheme (e.g. *trichter**förmig*** instead of *trichter**artig***, *glocken* instead of *glocken**förmig***) were the most frequent error type. Appendix 5 shows an overview of the number of lexical and phonological errors in repetition per patient.

3.5. Influence of Task Type

Inspection of the data suggests that the error type distribution predicted by the categorical account was more pronounced in reading than in repetition of number words whereas the opposite pattern was observed for other words (see Figure **2**). However, given the large number of patients who did not produce any error in at least one of the tasks we did not perform any inferential statistics.

4. DISCUSSION

In the present study, performance of aphasic patients in repetition, reading aloud, and writing to dictation of number words and other words was analysed with respect to the proportion of lexical and phonological errors. In general, we replicated the results of Messina *et al*. [1] and similar findings of other authors, showing that across all tasks patients as a group made more lexical errors with number words but more phonological errors with other words. However, a closer look at the data revealed that this dissociation of error types did not occur as clear-cut as could have been expected based on a categorical account: Unexpected errors (i.e. phonological errors for number words and lexical errors for words) did occur. Individual patients even produced the opposite pattern. Moreover, the distribution of error types was influenced in a gradual way by type of stimulus and task. This pattern of results casts doubts on a categorical explanation of the observed error type dissociation as proposed in previous studies [1, 15, 18]. However, this pattern seems compatible with an account based on more subtle differences between both types of words, which are based on gradually different parameter values of psycholinguistic variables. Finally, the observed pattern also seems to be consistent with a specific model of speech production of both types of words (WEAVER++ [23]).

By and large, we replicated the dissociation of error types found in previous studies, extending the evidence to reading aloud Arabic numbers and non-words. For some tasks and stimuli, the numerical dissociation found in the present study was as pronounced (repetition of words) or even more extreme (reading aloud number words) than reported by Messina *et al*. [1]. However, in two conditions (repetition of number words and reading aloud words) we found a numerically less pronounced dissociation, which in one occasion (repetition of number words) failed to reach significance. We would not like to put too much emphasis on the differences between studies. They may be due to different tests containing different stimuli[8] used with different patients in a different language (Italian vs. German). The failure to find significant differences in one of our conditions may be due to a lack of power, because six out of 15 patients did not produce any error in this condition. Moreover, the statistical procedures used are not directly comparable between studies: We used Wilcoxon signed-ranks tests, while Messina *et al*. [1] reported chi-square tests which do not take into account the variability among patients.

Analyses of individual cases revealed that the pattern found at the group level is only observed in a subset of patients. In repetition of number words, only seven out of fifteen patients showed the predicted pattern (i.e. more lexical errors) and only for one (Patient 21) of them the difference was significant (see Table **4**). However, another patient (Patient 6) produced only phonological errors in this task (i.e. the unexpected pattern) and the deviation from an equal probability of both error types was also significant.To us, it remains open how a categorical account could apply for this case. Even more principally, it remains unclear how the occurrence of any single "unexpected" error could be explained other than by the mere accident that phonological distortions may by chance lead to lexical errors. Note that errors categorised as lexical or phonological were *not* of the mixed type (e.g. *zwei* instead of *drei*, both items related lexically *and* phonologically) (for examples of errors see Appendix 3 and Appendix 4), thus making it very implausible to assume that errors which are superficially of the lexical type are actually phonological in nature. Moreover, formal or lexical errors have been repeatedly reported for the aphasic production of non-number words [28-31]. Therefore it seems unwarranted to predict that such errors should not occur. Finally, we have to admit that we are far from being able to predict for the tasks and stimuli at hand, which specific individual patient profiles should favour lexical or phonological errors.

Type of stimulus modulated the observed relation between lexical and phonological errors in a gradual way (see Figure **1**). For instance, in repetition the proportion of lexical errors increased from morphologically simple words over non-specific complex words, complex geometrical words to complex number words. This increase of lexical errors was paralleled by a decrease of the morpheme-based type-token ratio. It seems plausible to assume that morphemes which are repeated several times during a testing session may be confused more likely than morphemes which are only occurring once. Following this argument, morphologically simple words and complex number words as tested by Messina *et al*. [1] may mark extreme points on a continuum of psycholinguistic properties. They seem not to form two completely separate processing categories though, given that other variants of non-number words (non-specific complex words and geometrical words) are in between the extremes. In line with this interpretation, Dotan and Friedmann [16] found that some non-numerical types of stimuli (function words, letter names, morphological affixes) behaved like number words. Note, however, that we only intended to give an example of what sort of properties may affect error types and why. Yet, numerous variables may play their role here. It would clearly be beyond the scope of this paper to provide a comprehensive list of variables (e.g. stimulus type, task type, word length…) which may potentially influence the type of errors produced. A first hint in this respect is provided by Bencini *et al*. [18], who demonstrated that neither grammatical word class, nor word frequency, nor length in syllables or characters were significant predictors of the number of phonological errors in their patient. Yet, a systematic investigation for psycholinguistic variables affecting the error type distribution is still lacking.

The present data suggest that the proportion of error types may be modulated by task. While more lexical errors were produced in repetition than in reading aloud for number words, the opposite pattern was observed for other words. However, no inferential statistics could be performed here. Similarly, visual inspection of descriptive statistics provided by Dotan and Friedmann [16] also suggests that the distribution of error types may vary systematically between tasks: For example, the proportion of lexical/semantic errors

[8]Note for instance, that – in contrast to our study – stimuli used by Messinawere all morphologically simple [1]. This may have caused at least one part of the differences (see below).

for words seemed to be larger in naming than in reading or repetition. Yet, unfortunately no inferential statistics was reported on this issue either. While a modulation by task would create a challenge for the categorical account, this argument would be even more convincing, if the direction of task differences could be predicted and the specific mechanism behind these differences could be specified.

In sum, our data speak in favour of a gradual account for the explanation of different error type distributions observed for number words and other words. According to this account and consistent with the WEAVER++ model [23] number words display different psycholinguistic properties which increases their probability of leading to a lexical error. On the other hand, our data are a challenge for categorical accounts, which assume that number words and other words are processed based on different units in speech production. Clearly, the gradual account still has to be spelled out in detail. Further research will have to specify which kind of patient in response to which kind of stimulus will produce one type of error or another in which kind of task. Our data suggest an influence of task-type and stimulus-type. Further research will have to verify this influence and will have to specify influence of other psycholinguistic variables.

ACKNOWLEDGEMENTS

The present research was funded by a grant from the RWTH Aachen University Hospital (START grant number 690732) supporting F. Domahs and by a grant from the German Research Foundation DFG (grant WI 1804/6) supporting K. Willmes.

Appendix 1: Demographic and Clinical Data Describing the Patient Sample

patient ID	gender	age in years	months post onset	syndrome	additionalsymptoms
3	male	43	51	Broca	
6	male	60	1	non classifiable	
7	male	47	6	Broca	alexia
8	male	47	25	non classifiable	
10	male	51	27	transkortical	
14	male	46	80	non classifiable	dysathria / verbal apraxia
15	male	46	18	Wernicke	
17	female	37	40	Broca	
21	male	54	12	non classifiable	
25	male	65	41	Wernicke	
26	male	72	17	non classifiable	alexia, dysathria / verbal apraxia
36	male	49	8	non classifiable	
37	female	47	7	Wernicke	
39	female	54	71	rest-aphasia	verbal apraxia, buccofacialapraxia
40	female	46	15	Broca	

Appendix 2: Number of Lexical and Phonological Errors Per Patient and Task

Patient ID	Repetition of Number words		Reading aloud number words		Reading aloudarabicnumbers		Writing to dictation of arabic numbers		Writing arabic numbers to spoken number words		Repetition ofwords		Reading aloudwords		writing words to dictation		Reading aloud non-words	
	lex. errors	phon. errors	lex. errors	phon. errors	lex. errors	phon. errors	lex. errors	phon. errors	lex. errors	phon. errors	lex. errors	phon. errors	lex. errors	phon. errors	lex. errors	phon. errors	lex. errors	phon. errors
3	0	1	0	0	0	0	8	0	1	0	0	8	0	11	0	6	0	10
6	0	6	3	0	1	3	7	0	0	0	1	3	0	18	0	1	0	15
7	0	0	0	0	3	0	7	0	0	0	0	5	1	1	0	4	0	8
8	1	0	2	0	1	0	6	0	0	0	0	3	0	1	0	1	0	5
10	0	0	1	0	0	0	8	0	4	0	0	0	0	2	0	3	0	1
14	1	0	1	0	1	0	4	0	0	0	0	6	1	2	0	1	0	4
15	4	0	0	0	1	0	11	0	0	0	0	6	6	19	1	4	0	17
17	0	0	3	0	8	0	6	0	6	0	0	2	7	6	0	5	2	0
21	6	0	3	1	0	0	8	0	0	0	0	4	5	6	1	3	0	10
25	0	0	1	0	3	0	6	0	6	0	0	5	0	0	0	6	0	6
26	1	0	3	0	8	0	12	0	1	1	0	8	3	14	0	5	1	7
36	4	0	2	0	3	0	3	0	0	0	0	2	0	0	1	1	0	2
37	1	0	3	0	1	0	9	0	0	0	0	8	0	7	1	3	1	10
39	0	0	4	0	3	0	1	0	0	0	0	5	0	4	0	1	0	9
40	0	0	0	0	0	0	8	0	1	0	0	0	0	0	0	0	0	8
overall	18	7	26	1	33	3	104	0	19	1	1	65	23	91	4	44	4	112

Appendix 3: Examples of Phonological Errors in Number Words

Patient ID	Task	Target	Response (correctresponse)
3	Repetition number words	46	zwitzig (sechsundvierzig)
6	Repetition number words	103	hunderthei (hundertdrei)
		64	vier und nechtig (vierundsechzig)
		82	zweiunachtig (zweiundachtzig)
		46	fermisibnet (sechsundvierzig)
		105	untingtzne (hundertfünf)
		109	hunderteuneuneueun(hundertneun)
	Reading Arabic numbers	71	fffPernze (einundsiebzig)
		60	sechsie (sechzig)
		850	kompe ne (achthundertfünfzig)
26	Reading number words	SIEBZIG	siebet (siebzig)

Appendix 4: Examples of Lexical Errors in Words

Patient ID	Task	Target	Response
6	Repetition words	hohl	oben
7	Reading words	Zigarette	Ziel
14	Reading words	Zeichnung	Zigarette
15	Reading words	Gas	Rad
		Unterlage	unterrasieren
		Spur	Wurst
		Feile	Felle
		Nager	Laus
	Writing words	Leichtmetallleiter	Tal
17	Reading words	Rad	Fahrrad
		Friedhof	Huf
		Zigarette	rauchen
		Zeichnung	malen
		Ruhe	nicht stören
		Pirat	Kapitän
21	Reading words	Friedhof	Radio
		Zeichnung	Zeitung
		Lastwagen	ein Rathaus
		Schaumgummipolster	Weingummipolster
		Quark	Quirl
26	Reading words	Berg	braun
		Locke	Lauch
		Sportler	fest
36	Reading words	Künstler	Schauspieler
37	Reading words	Heiterkeit	Schere

Appendix 5: Number of Lexical and Phonological Errors in Repetition Per Patient and Stimulus Type

Patient ID	Simplex words		Complex words		Geometric Words		Complex number words	
	lex. errors	phon. errors	lex. errors	phon. errors	lex. errors	phon. errors	lex. errors	phon. errors
3	0	8	0	5	2	2	0	0
6	1	3	0	5	1	9	0	6
7	0	5	0	2	0	1	0	0
8	0	3	0	5	1	0	1	0
10	0	0	0	0	0	0	0	0
14	0	6	1	4	0	1	0	0
15	0	6	1	4	0	1	3	0
17	0	2	0	1	0	0	0	0
21	0	4	1	3	2	3	6	0
25	0	5	0	0	0	0	0	0
26	0	8	0	6	0	0	1	0
36	0	2	2	3	2	0	4	0
37	0	8	1	4	0	0	0	0
39	0	5	0	1	0	0	0	0
40	0	0	0	0	0	0	0	0
overall	1	65	6	43	8	17	15	6

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Received on 19-11-2013 Accepted on 29-11-2013 Published on 30-11-2013

DOI: http://dx.doi.org/10.12970/2311-1917.2013.01.01.3