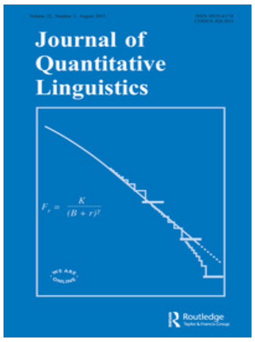

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Zipf's Law in Non-Fluent Aphasia*

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ABSTRACT

We studied Zipf's law in the spontaneous speech of four people with non-fluent aphasia, and compared that to the spontaneous speech of four speakers from the Corpus of Spoken Dutch. Our results show no worse fit to Zipf's law for aphasic compared to healthy speech but only a difference in slope. We argue that the fact that Zipf's law is unaffected in people with aphasia, who suffer from problems with word retrieval rather than word storage, suggests that it is the organization of the mental lexicon that renders speech to conform to Zipf's law and not the word retrieval system.

1. INTRODUCTION

Word frequencies in natural language texts typically conform to a power law called Zipf's law. But despite this ubiquitous presence, almost a century after its first discovery it is still unclear as to *why* Zipf's law occurs. A question closely linked to why it occurs is the question where it comes from, in other words, the question where Zipf's law originates in the process of natural language production. This is the question that is addressed in this study.

Zipf's law is present in all natural language output, which means that there are two likely sources for Zipf's law. These are the system responsible for the *selection and retrieval* of words, and the system responsible for the *storage* of words. These hypotheses can be viewed as a *processing* and a *knowledge* approach.

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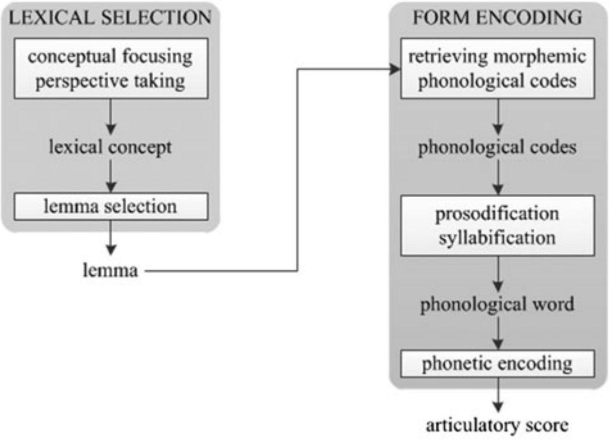

Fig. 1. Levelt's model of lexical access (Levelt, 2001).

The processing approach locates the source for Zipf's law in the system for selection and retrieval of words for speech production. This approach is best illustrated by means of a model of lexical retrieval. One of the most well-known models of lexical retrieval is Levelt's model (see Figure 1, e.g. Levelt, Roelofs, & Meyer, 1999). This model consists of two sub-systems. The first sub-system is that of (sub)lexical selection, which consists of perspective taking and lemma selection. The second sub-system is that of form encoding, which consists of the retrieval of morphemic and phonological codes, prosodification and syllabification and phonetic encoding. In this model, Zipf's law would have to be the result of the functioning of the system of lexical selection, the stage at which lemmas are retrieved. It could thus either be placed in the component for conceptual focussing and perspective taking, or in the component for lemma selection.[1]

Zipf's original explanation for his law in terms of least effort (Zipf, 1949) would most likely concern this system of word selection and retrieval. A more exact characterization of the principle of least effort was provided by Ferrer i Cancho and Solé (2003), who mathematically showed that

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[1] One could also argue that the relevant phase is that of the sub-system of form encoding, since in the traditional formulation of Zipf's law not lemma frequency but form frequency is considered. However, the fact that Zipf's law is also present in lemma counts (e.g. Hatzigeorgiu, Mikros, & Carayannis, 2001, Gelbukh & Sidorov, 2001) renders this explanation unlikely.

Zipf's law can theoretically follow from the critical point between minimised speaker and hearer effort, measured in entropy.

The knowledge approach, on the other hand, locates the source for Zipf's law in the system for the storage of words, which is the mental lexicon. The rationale here is that words are stored in such a way that their retrieval automatically results in Zipf's law. Evidence that the lexicon is in fact organized in such a way follows, for instance, from the work by Steyvers and Tenenbaum (2005). Steyvers and Tenenbaum constructed models of semantic growth based on different sources of natural language (WordNet, Roget's thesaurus and word association norms). All their models resulted in small world, scale free networks, which means that the number of connections between words follows a power law (of which Zipf's law is a particular instance). Random walks through networks that are organized in this way automatically generate output that follows Zipf's law (Masucci & Rodgers, 2006; da Fontoura Costa, Sporns, Antiqueira, das Graças Volpe Nunes, & Oliveira, 2007). It is likely that activation spreads through the lexicon in a way that closely resembles random walks. It would then follow that Zipf's law is the inevitable result of retrieving words from a lexicon with a small world, scale free structure.

Can these two hypotheses be disentangled? We believe they can, by analysing speech from people with a selective impairment in either the system for word retrieval or in the system for word storage. This profile is met by people with non-fluent aphasia: their impairment can be located in the system for word retrieval, while their system of word storage is unaffected.

Aphasia is an acquired language disorder, most often acquired after a stroke. It is a disorder that can manifest itself in many different ways, with many different kinds of language impairments such as paraphrases, agrammaticality or comprehension difficulties. However, the problem encountered most often is that of word finding difficulties: people with aphasia are unable to retrieve the words from their internal lexicon. These problems have been suggested to arise due to processing deficits (Avrutin, 2006; Burkhardt, Avrutin, Piñango, & Ruigendijk, 2008; Van Ewijk, 2013). In healthy individuals, syntactic computations are used to build information structure, and thus to encode messages. This component, however, has been damaged in aphasic individuals. Using syntax has thus become much more costly and where possible alternative options for information encoding are deployed. Importantly, their impairment does not involve a loss of knowledge, neither of syntactic operations nor of lexical elements (Avrutin, 2006).

Prior to stroke, aphasic speakers used to be able to use language in the normal way. It can therefore be assumed that before their brain damage their speech conformed to Zipf's law, as does any other natural language text. The question is whether that is still the case now that they suffer from aphasia. In this respect it is interesting to analyse both full samples and lexical and grammatical words separately, because people with aphasia are well-known for their problems with grammatical elements (e.g. Code, 2010). Any disruption in samples containing both classes of words can thus be due to a problem with both lexical and functional elements or to a problem with functional elements only.

Even though Zipf's law has been shown to apply to every natural language text in every language for which it has been tested, it is hardly ever investigated in language impaired populations. To our knowledge, only Howes and Geschwind (Howes, 1964; Howes & Geschwind, 1964) investigated word frequency distributions in people with aphasia. Their results indicate that speech from people with aphasia conforms to Zipf's law, albeit with a different slope. Unfortunately, they did not use the traditional formulation of Zipf's law to study the word frequency distribution, but a cumulative version concerning the percentage of words that occur with frequencies up to and including each frequency value. This formulation is not very sensitive: disruptions in the higher frequency classes are easily concealed if the lower frequency classes do follow the Zipfian distribution. Another issue is that their samples contain words from both lexical and grammatical categories.

The goal of the current study was thus to test whether speech from people with aphasia conforms to Zipf's law, and whether there is a difference in their speech between grammatical and lexical elements. Two factors are distinguished: the fit to the power law, which indicates whether or not the text conforms to Zipf's law; and the slope of the power law, which indicates the diversity of the words used in the sample.

Two possible outcomes are of interest. The first possibility is that we find that speech from people with aphasia displays a poorer fit to Zipf's law than speech from healthy speakers. This would be an indication that Zipf's law is due to the characteristics of the system for lexical retrieval, which is affected in people with aphasia. The second possibility is that we find no difference in fit to Zipf's law between healthy and aphasic speech. This would be an indication that the impairment in people with aphasia has no influence on Zipf's law, and that Zipf's law originates in the mental lexicon.

2. METHODS

2.1 Participants

Four non-fluent aphasic participants were recruited at the aphasia centre in Tilburg, the Netherlands. They were all Dutch monolingual speakers and had no prior history of dementia or other memory deficits. None had a significant history of other neurological or psychiatric illness or drug/alcohol abuse. All participants had normal, or corrected to normal, hearing and suffered a unilateral lesion resulting from a cerebrovascular accident. The token test (part of the Dutch AAT, Graetz, De Bleser, & Willmes, 1992) was administered to determine the presence of aphasia. As suggested by Heesbeen (2001) a cut-off score of seven errors was used for the diagnosis of aphasia. Presence of word finding difficulties in all four participants was reported by their local speech therapist and confirmed by analysis of spontaneous speech samples by one of the authors and by an independent speech and language therapist. Their spontaneous speech was recorded and transcribed.

For comparison, speech samples from four healthy speakers from the Corpus of Spoken Dutch (CGN-consortium, 2004) were selected. The speakers from the CSD were matched on sex to the aphasic speakers, and approximately on age. Two conversations were chosen from the CSD, both with two speakers in it, so that each speaker could be matched with an aphasic speaker. The speakers that were in the same conversation were N01004 and N01005, and N01010 and N01011. All speaker details are given in Table 1.

2.2 Procedure

Speech from the aphasic participants was recorded during an unstructured interview, which started with the question of how they got their aphasia and continued as a free conversation about multiple topics. The speech samples were thus not connected streams of speech, but were interspersed by speech from the interviewer. Only speech from the patient was analysed. All conversations were recorded on video and orthographically transcribed in CHAT-format (MacWhinney, 2000).

For the healthy speakers, the conversations that were chosen for analysis were recorded during natural conversation (as opposed to speeches, news bulletins, etc.). Conversations were converted to CHAT-format for further analysis. In each analysis, the speech from the conversation partner was ignored.

Table 1. Speaker details.

Non-fluent aphasic speakers						Healthy speakers		
Speaker	Sex	Age	Time post onset	Cause	Token test score (raw)*	Speaker	Sex	Age
EvdL	f	59	10 years, 4 months	Stroke	50	N01011	f	34
JJ	f	63	7 years, 3 months	Multi-infarct syndrome	24	N01005	f	56
JvdH	f	36	6 years, 3 months	Stroke	9	N01004	f	29
PH	m	33	3 years, 10 months	Stroke after trauma	50	N01010	m	30

*Scores over 13 are seen definite presence of aphasia, scores below 7 as no or very little aphasia.

2.3 Analysis

The parameters of Zipf's law are highly dependent on text size (e.g. Baayen, 2001). The samples that are analysed should thus always contain the same number of tokens for each speaker. However, a distortion of Zipf's law or a difference in slope for aphasics does not necessarily reflect any deep property of aphasic speech, but could also be a mere by-product of the smaller productive vocabulary of aphasic speakers (see also Baixeries, Elvevåg, & Ferrer-i-Cancho, 2013, for the same argument in child language). To control for this, two sets of analyses are reported: one in which the number of tokens for each speaker is kept constant (hereafter: *token analysis*), and a second in which the number of types per speaker is kept constant (hereafter: *type analysis*). The types and tokens for analysis are selected by means of prefix: for the token analysis, the first x tokens were selected; for the type analysis, the first y types were selected, after which their frequency amongst the first x tokens was counted (where x and y depend on the analysis under consideration, see below for the exact values). The token set thus represents the most natural text: all words that were uttered, up to a certain cut-off point, are analysed. The type set does not necessarily represent a natural text: the frequencies of the first y types are counted, but there were in most cases other types in the sample that are now neglected.

Both in the type set and in the token set three analyses are performed: one for all words (*all words analysis*), one for lexical words only while excluding grammatical words (*lexical words analysis*) and one for grammatical words only while excluding lexical words (*grammatical words analysis*). Nouns, verbs, adjectives, adverbs and full verbs were considered lexical words; prepositions were split according to their function in the sentence (grammatical or lexical); all other parts of speech were considered grammatical words.[2] Numerals were excluded.[3] If words were used to fill pauses then these were included in the counts; utterances like "uhm" and "uh" were excluded. Orthographically identical words of different word categories were counted as separate words.

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[2] We are aware that the boundary between function words and lexical words is by no means crisp, and has been a topic of discussion. In fact, this boundary is probably rather continuous than dichotomous. Nevertheless, it cannot be denied that there is some distinction between classes of words, and we believe this distinction to be useful enough for our current purposes. See also Popescu, Altmann, and Köhler (2010), for a similar argument.

[3] Numerals seem to be dissociated in memory from other word categories (Cohen, Dehaene, & Verstichel, 1994; Roux, Lubrano, Lauwers-Cances, Giussani, & Démonet, 2008).

The frequency lists in the token set contained the same number of tokens for all participants, equal to the number of words in the smallest sample: 352 tokens for the full text; 152 tokens for the lexical words analysis; and 200 words for the function words analysis. The number of types thus differed per person; these numbers can be found in Table 4. The frequency lists in the type set contained the same number of types for all participants, equal to the numbers in the smallest sample: 95 types (sampled from the first 352 tokens) for the full text; 60 types (sampled from the first 152 lexical tokens) for the lexical words analysis; and 28 types (sampled from the first 200 grammatical tokens) in the grammatical words analysis.[4]

A choice was made to include as many words as possible per analysis while keeping the number of words that was analysed per person the same. This means that comparisons can be made between groups, but not directly between analyses, because of the dependence of the parameters of Zipf's law on text size.

Rank and frequency were logarithmically transformed, after which the fit and coefficient of Zipf's law were calculated through linear regression. In this linear regression analysis, cases were weighted for frequency to balance the large influence from the large class of low-frequency words on the line fitting.[5]

Significance is tested for by means of an exact permutation test. This test and not the well-known *t*-test was used, because the distribution of values is unknown and not necessarily normally distributed. It should be noted, however, that the number of participants was very low. Statistical tests, therefore, are only a tentative indication of the strength of the effect.

3. RESULTS

Average values are reported in Table 2 and Table 3. Detailed results per speaker are provided in Table 4. Rank-frequency plots are provided in Figure 2 for the type analysis and Figure 3 for the token analysis.

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[4] The speaker with the smallest number of functional elements used a larger number of lexical types. This explains why the smallest number of different types, irrespective of the functional /lexical distinction, was 95, not 88 (lexical + grammatical sample size).

[5] This method might not be optimal (e.g. Clauset, Shalizi, & Newman, 2009), but it has been frequently applied to determine the coefficients of Zipf's law (e.g. Köhler, 2002; Tuzzi, Popescu, & Altmann, 2009) and therefore allows for comparisons with previous work on this topic. In any case, any systematic errors that have arisen from this method exist for both groups and do therefore not detract from the results and conclusions.

Table 2. Adj. r^2 values.

	TOKEN ANALYSIS			TYPE ANALYSIS	
	Adj. R^2			Adj. R^2	
	Aphasics		Controls	Aphasics	Controls
All words	0974		0957	0967	0935
Lexical words	0966	#	0907	0965	0925
Grammatical words	0943		0911	0920	0870

$^{\#}p < 0.05$, sign. differences in the unexpected direction (aphasic speech shows a better fit).

Table 3. Average parameter values for token-set of analyses.

	TOKEN ANALYSIS			TYPE ANALYSIS		
	Coefficient (St. error)			Coefficient (St. error)		
	Aphasics		Controls	Aphasics		Controls
All words	0834	*	0677	0863		0724
	0012		0011	0016		0019
Lexical words	0714	*	0463	0752	*	0554
	0015		0014	0018		0020
Grammatical words	0997	*	0731	1006		0754
	0037		0028	0053		0053

$^{*}p < 0.05$.

3.1 Fit

In all analyses, a good fit to Zipf's law is observed. The lowest fit that was observed in any analysis was adj. $R^2 = 0.87$ in the grammatical words of healthy speakers in the token analysis. In all other cases adj. $R^2 > 0.9$. In no analysis was the fit to Zipf's law of aphasic speech lower than that of healthy speech. In fact, the fit of lexical words in the type analysis was significantly better in aphasic speech than in healthy speech ($p = 0.029$), and in the token analysis a trend in the same direction was found ($p = 0.057$).[6]

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[6] This difference is probably due to the lower number of low frequency words in the aphasic speech samples.

Table 4. Detailed results per speaker.

			All words					Lexical words					Grammatical words				
			Types	Tokens	Coef.	St. error	Adj. R^2	Types	Tokens	Coef.	St. error	Adj. R^2	Types	Tokens	Coef.	St. error	Adj. R^2
TYPE ANALYSIS	Aphasics	JJ	95	282	0.848	0.014	0.975	60	117	0.704	0.018	0.961	28	155	1.009	0.047	0.945
		EvdL	95	342	0.834	0.018	0.957	60	152	0.851	0.014	0.985	28	193	0.881	0.072	0.846
		JvdH	95	296	0.811	0.020	0.948	60	129	0.712	0.023	0.943	28	176	1.010	0.060	0.912
		PH	95	352	0.958	0.010	0.990	60	132	0.740	0.017	0.970	28	200	1.123	0.033	0.977
	Controls	N01005	95	253	0.825	0.014	0.972	60	89	0.614	0.023	0.922	28	135	0.923	0.041	0.949
		N01011	95	258	0.647	0.022	0.901	60	88	0.488	0.021	0.903	28	112	0.673	0.066	0.791
		N01004	95	270	0.720	0.019	0.941	60	100	0.587	0.015	0.961	28	135	0.727	0.045	0.907
		N01010	95	267	0.704	0.021	0.926	60	102	0.524	0.021	0.914	28	138	0.693	0.059	0.834
		Aph.av.	95	318	0.863	0.016	0.967	60	132.5	0.752	0.018	0.965	28	181	1.006	0.053	0.920
		Cont. av.	95	262	0.724	0.019	0.935	60	94.75	0.554	0.020	0.925	28	130	0.754	0.053	0.870
		$p =$			0.057	NS	NS	87	152	0.029	NS	0.057	57	200	0.057	NS	NS
TOKEN ANALYSIS	Aphasics	JJ	144	352	0.780	0.009	0.983			0.637	0.014	0.960			0.944	0.017	0.981
		EvdL	101	352	0.827	0.017	0.961	60	152	0.851	0.014	0.985	33	200	0.913	0.063	0.866
		JvdH	137	352	0.770	0.013	0.964	76	152	0.671	0.017	0.952	45	200	1.010	0.035	0.949
		PH	95	352	0.958	0.010	0.990	76	152	0.696	0.015	0.968	28	200	1.123	0.033	0.977
	Controls	N01005	169	352	0.736	0.010	0.970	120	152	0.475	0.017	0.871	63	200	0.825	0.020	0.964
		N01011	172	352	0.623	0.012	0.940	114	152	0.418	0.014	0.894	67	200	0.647	0.032	0.859
		N01004	159	352	0.682	0.011	0.962	105	152	0.496	0.012	0.944	64	200	0.726	0.025	0.932
		N01010	162	352	0.665	0.011	0.956	106	152	0.463	0.014	0.917	58	200	0.724	0.034	0.890
		Aph. av.	119.3	352	0.834	0.012	0.974	74.75	152	0.714	0.015	0.966	40.75	200	0.997	0.037	0.943
		Cont. av. 165.5	352	0.677	0.011	0.957	111.3	152	0.463	0.014	0.907	63	200	0.731	0.028	0.911	
		$p =$			0.029	NS	NS			0.029	NS	0.029#			0.029	NS	NS

[#] The difference is in the unexpected direction: Aphasics show a better fit/smaller standard error than healthy speakers.

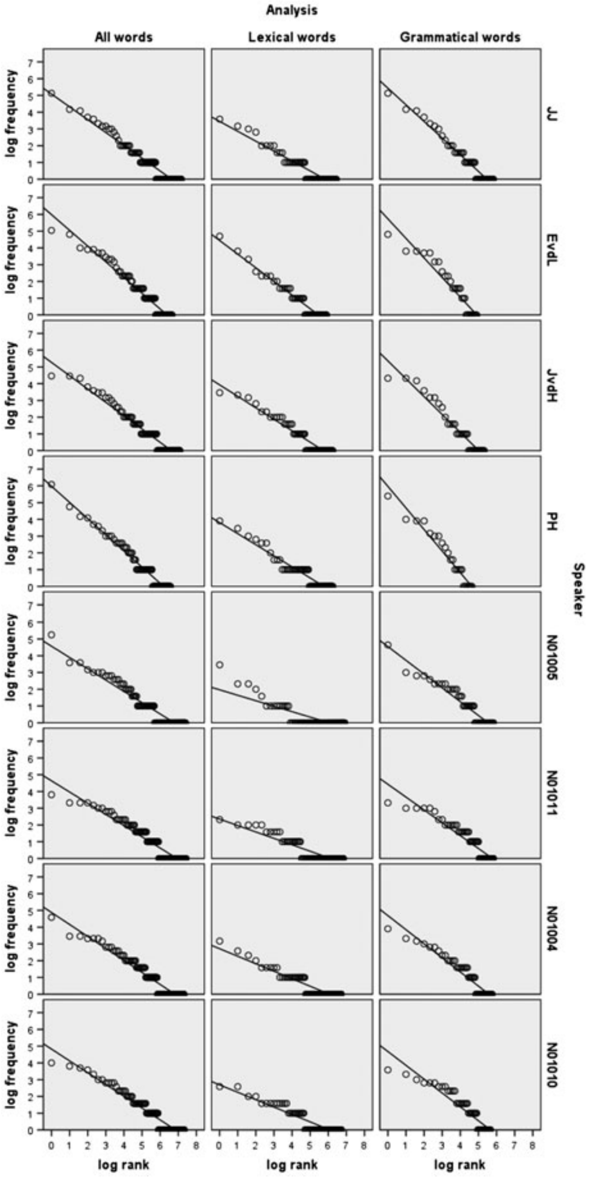

Fig. 2. Zipf's law in type samples.

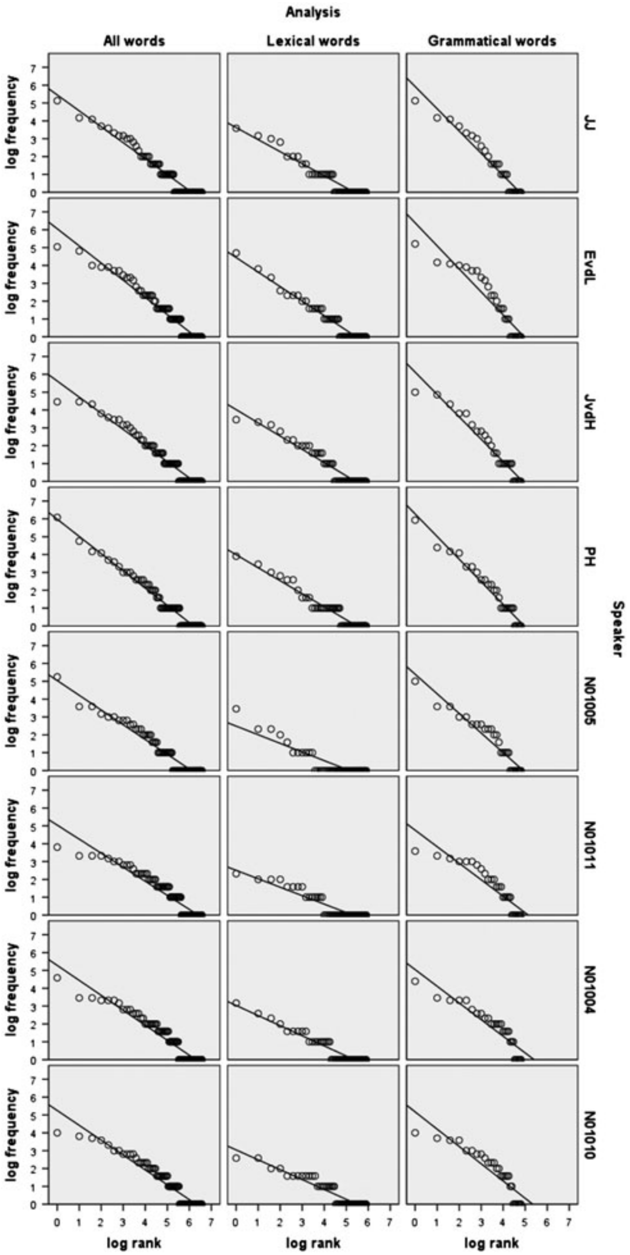

Fig. 3. Zipf’s law in token samples.

3.2 Slope

In the token analysis, the slope of Zipf's law is significantly higher ($p = 0.029$) for aphasic speech than for healthy speech for all three groups of words. In the type analysis this difference was also found in the lexical words ($p = 0.029$), and in the all words and grammatical words samples the difference approached significance ($p = 0.057$). No differences in standard errors were found.

For a graphical representation of the slope values and standard errors, see Figure 4.

3.3 Comparison with the traditionally reported value

As discussed above, the typical values of the parameters of Zipf's law is taken to be $\alpha \approx 1$. However, for the healthy speakers in all analyses reported here an α lower than that was found. In the most natural speech sample, the all words sample in the token analysis, it was found that on average $\alpha = 0.677$.[7] Only for grammatical words in aphasic speech $\alpha = 1$ was found.

This difference between typical values and the values found in the current study is taken to be due to the small text sizes and the fact that verbal (as opposed to written) texts were used. This difference stresses the importance of the use of a control group if impaired populations are investigated: clearly, the typically reported values do not always apply, and cannot always be used as a benchmark.

4. DISCUSSION

Our aim was to test whether speech from people with aphasia conforms to Zipf's law, and whether there is a difference in their speech between grammatical and lexical elements. Our results show that, despite their evident problems with speech production, speech from people with non-fluent aphasia conforms to Zipf's law. Fit of Zipf's law was in no analysis worse for aphasic speakers than for healthy speakers. The only difference that was observed was a difference in slope of their rank-frequency distribution. This different slope is in line with the problems that these speakers had: it

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[7] Because of the small sample of four healthy speakers, significance of this difference was not tested.

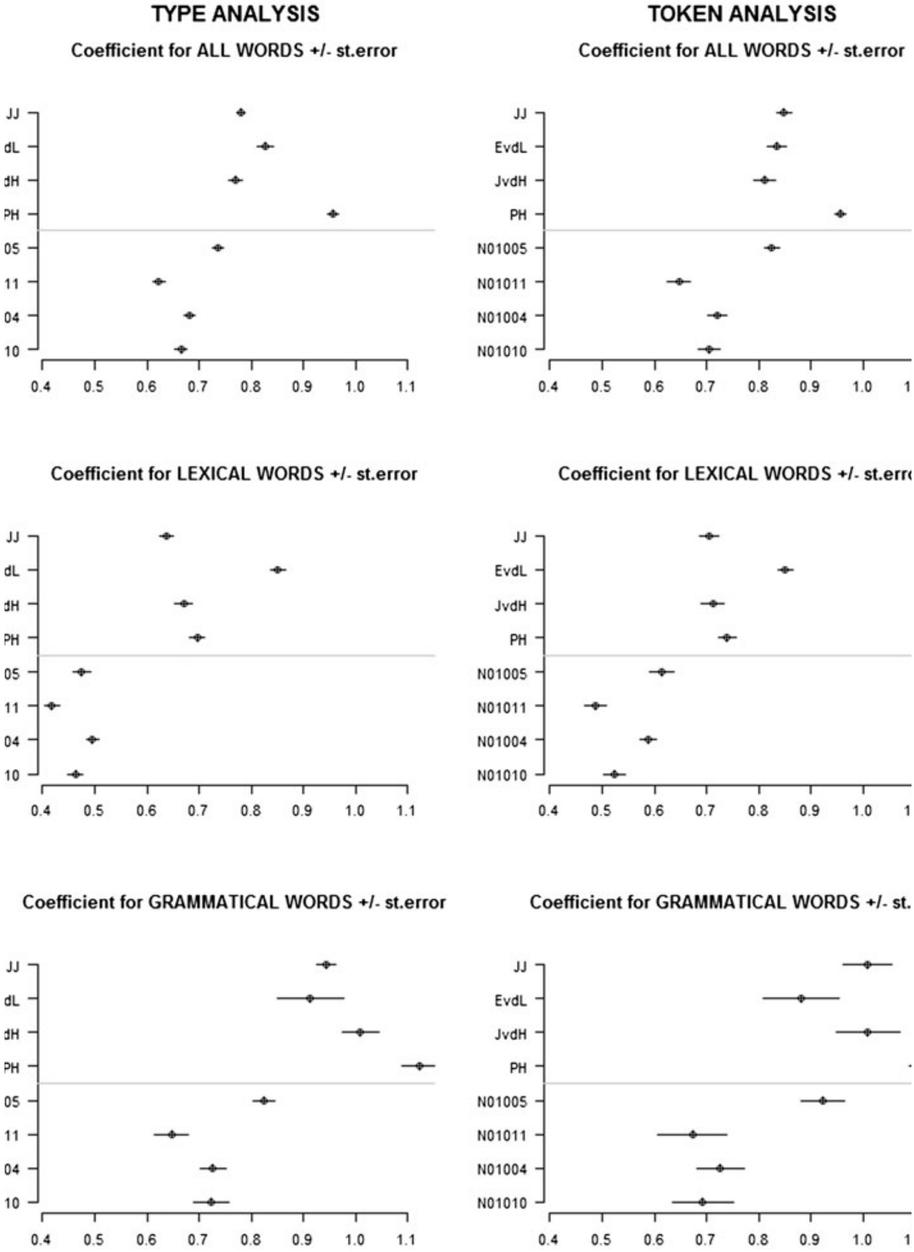

Fig. 4. Coefficients per speaker. Bars indicate standard error.

indicates that aphasic speakers use fewer different types, and use those types that are used more frequently.

These findings shed light on the question outlined above, which was whether Zipf's law originates in the system for word retrieval or in the system for word storage. The fact that Zipf's law is unaffected in people with aphasia, who suffer from problems with word retrieval rather than word storage, suggests that it is in fact the organization of the mental lexicon that renders speech to conform to Zipf's law. Spreading activation through the lexicon, organized as a small world, scale free network, is then what causes speech output to conform to Zipf's law.

One conjecture to this could be that the choice of words is not random, but dictated by the discourse topic (lexical words) and syntax (grammatical words). However, within this predetermined framework speakers have some room to manoeuvre and choose words and syntactic constructions to their liking. It seems to be the case that speakers unconsciously structure their speech such that it conforms to Zipf's law. Importantly, they cannot refuse to do so: they cannot consciously distort Zipf's law. This again suggests that it is indeed a hardwired property of the language faculty that causes Zipf's law.

Usually, Zipf's law is investigated in very large text samples such as books. Our samples are markedly smaller than that, and besides consist of spontaneous speech instead of written texts. It is therefore far from obvious that our samples should conform to Zipf's law. However, in all analyses it was found that Zipf's law applies. These findings provide more proof of the universality of Zipf's law.

If our hypothesis is correct then it would be predicted that speech from people with an intact processing system but an impaired lexicon would not conform to Zipf's law. One group of speakers one could think of is formed by people with a semantic variant of primary progressive aphasia (SvPPA), also referred to as semantic dementia. People with SvPPA have impaired performance on measures that depend on intact semantics. This means that they experience difficulties with tasks like picture and object naming, single word comprehension and category naming. However, these patients do relatively well on measures of grammar, phonology, visual-spatial skills and number knowledge (Bonner, Ash, & Grossman, 2010). In other words, their impairment seems to be limited to word storage (both the lexemes and the associated semantics), but do not seem to involve the system for word retrieval, as is evident from the fact that their syntactic knowledge is unimpaired. If our hypothesis is correct then it would be predicted that speech from patients with SvPPA does not conform to Zipf's law. Future research is necessary to provide an answer to this.

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DISCLOSURE STATEMENT

The authors declare that there are no conflicts of interest.

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