Word Retrieval in Acquired and Developmental Language Disorders: A Bit more on Processing.

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Word Retrieval in Acquired and Developmental Language Disorders: A Bit more on Processing.

Woordvinding in Verworven en Aangeboren Taalstoornissen: Het Belang van Verwerkingscapaciteit

(met een samenvatting in het Nederlands)

Proefschrift

ter verkrijging van de graad van doctor aan de Universiteit Utrecht op gezag van de rector magnificus, prof.dr. G.J. van der Zwaan, ingevolge het besluit van het college voor promoties in het openbaar te verdedigen op vrijdag 13 september 2013 des middags te 12.45 uur

door

Elisabeth van Ewijk

geboren op 25 september 1982 te Wageningen

Promotoren: Prof. dr. S. Avrutin
Prof. dr. F.N.K. Wijnen

Voor mijn ouders

TABLE OF CONTENTS

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ABBREVIATIONS

AAT	Akense Afasie Test
AIM	Attention based on Information Maximization
CGN	Corpus Gesproken Nederlands
CVA	Cerebral Vascular Accident
Df	Degrees of Freedom
DP	Determiner Phrase
hCVA	Haemorrhagic Cerbral Vascular Accident
iCVA	Ischaemic Cerebral Vascular Accident
ICD-10	International Classification of Diseases – version 2010
Freq	Frequency
FF	Figural Fluency
GLM	Generalised Linear Model
KLdiv	Kullback-Leibler Divergence
METC	Medical Ethical Committee
MLU	Mean Length of Utterance
NP	Noun Phrase
lnRT	Natural Logarithm of the Reaction Time
Perc	Percentage
PWA	People with Aphasia
RT	Reaction Time
SD	Standard Deviation
SLI	Specific Language Impairment
SLT	Speech and Language Therapist
TD	Typically Developing
TPO	Time Post Onset
TT	Token Test
VU	Verbal Utterances
WHO	World Health Organization
WM	Working Memory

1 GENERAL INTRODUCTION

Language is the most important communicative tool of the human species. Children acquire language in a seemingly effortless fashion and by the time we reach adulthood we all have a vocabulary of words engrained in our brain of around 50000 words (Crystal, 2008). In conversation we address this giant dictionary with staggering speed and accuracy. Occasionally we get a glance at the complicated process of finding a word's meaning and sounds within this vast network when we experience the tip-of-the-tongue phenomenon ("I know the word has 3 syllables and starts with an s") or when fatigued or intoxicated the wrong word is selected; the well-known (Freudian) slip-of-the-tongue ("*We need laws that protect everyone. Men and women, straights and gays, regardless of sexual perversion…, ah…, persuasion*" New York Congresswoman Bella Abzug, quoted in Young, 1999). For healthy adults these occasional word finding difficulties are sometimes frustrating, occasionally embarrassing and often amusing, but overall do not interfere with effective communication as they occur sporadically. If however, finding the right word becomes problematic for the majority of words one wants to utter, communication is hugely affected. This is the daily reality for most adults with aphasia and many children with specific language impairment (SLI). One of the most interesting questions regarding the word finding difficulties of speakers with a language disorder is whether the words, due to brain damage or developmental difficulties, are missing all together, or whether they are present but difficult to retrieve. Throughout this thesis I will argue that the vocabulary of language impaired individuals is present, but that due to processing difficulties they have severe problems selecting the correct word from all words in the lexicon. In this first chapter I provide a general introduction to the key concepts of this thesis. I begin with a short description of information theory. Information theory will provide the mathematical framework used to explain complexity of words in general and the effect of complexity on language processing in language impaired individuals throughout this thesis. I give a short overview of the history of information theory, its basic concepts and possible applications to communication and language. I then provide a description of aphasia and its key features, after which I briefly touch upon the developmental language disorder SLI. In section 1.5 I formulate the main research questions. Section 1.6 discusses recruitment and selection of participants and section 1.7 deals with medical ethical aspects of this project. In 1.8 I provide an overview of the rest of this thesis.

1.1 Information Theory

1.1.1 Why Information Theory?

It is very likely that before opening this book, the reader had never heard of information theory. In fact, before embarking on this PhD project, *I* had never heard of information theory. I did however feel that current linguistic approaches to aphasia, in particular those that claim (grammatical) knowledge is lost or broken, could not explain the language of the aphasic patients I work with. With specific instructions, or under specific circumstances these patients *are* able to perform linguistic tasks that they otherwise find very hard. It was therefore clear to me that processing of some form was the culprit in the language difficulties of most of these patients. “Processing” however is one of the most underspecified concepts in aphasia literature. What does it actually mean to have limited processing capacity and crucially, how do we measure this? This is where, once I got my head around the math, information theory proved to be a fruitful framework.

In research on healthy speakers there has been a growing interest in the use of information theory in the last few decades. John Goldsmith at the University of Chicago has been working on morphology and phonology within an information theoretic paradigm (cf. Goldsmith, 2011); John Hale and colleagues at Cornell University have used information theory to explain syntactic phenomena such as the garden path sentence (cf. Hale, 2006); Jason Riggle at the Chicago Language Modelling Lab used information theory to look at the role of similarity in non-local dependencies (cf. Goldsmith & Riggle, 2012); Andrea Sims at Ohio State University uses information theory to investigate paradigmatic morphology (cf. Sims, 2009) and in Europe Ramon Ferrer I Cancho at the Universitat Politecnica de Catalunya and Fermin Moscoso del Prado, Petar Milin, Aleksander Kostic and Harald Baayen have been the main proponents of information theory in linguistic research. All of these research projects have in common that they look at the effect of (reducing) uncertainty in processing of language.

1.1.2 Main Concepts of Information Theory

Before we explore the history of information theory, its detailed principles and application to language processing it is useful to start this section with an example to explore exactly what "information" entails. The word information has become so engrained in our everyday vocabulary that it is important to determine the concept of information as used in information theory.

Within information theory when we measure information we are only concerned with the *amount* of information that has been acquired. The *value* of the information is not important. Information is something we get when someone or something "tells" us something we did not know before. For example if I look at my watch when I already know what time it is, the message my watch "tells me" gives me no information. Or as Garner (1952) suggests:

there was no *uncertainty* about that particular fact beforehand. Information exchange only occurs when there is an amount of uncertainty and the amount of information exchange is in fact determined by the amount of uncertainty.

For example: imagine a roulette wheel consisting of only one circular red unnumbered pocket covering the entire wheel. When the croupier spins the ball around the track there is no uncertainty about the pocket the ball will end up in, thus no information is conveyed. If however, the wheel has two equal sized pockets, one black and one red, there is a degree of uncertainty and we will gain information when the ball falls into one of the pockets. Information can thus be seen as the reduction of uncertainty. The uncertainty about the outcome is closely related to the number of possibilities that exist. For example, if we add pockets with the numbers 1-32 to the roulette wheel, the level of uncertainty about where the ball will end up is much greater than when we just have one big red and one black pocket.

Imagine we stay at the simple red/black wheel for two spins. Each spin has two possible outcomes and two spins have four possible outcomes (RR RB BB BR). So if one spin gives 2 units of information, then each successive spin should give us that much more information. However, if we stay for another spin, this third spin gives us 4 times the amount of information as one single spin (RRR RRB RBB RBR BRB BRR BBR BBB). We can thus not simply use the number of possible outcomes of an event as a measure of information. Uncertainty is therefore measured in logarithms:

[1] $$U = \log k$$

where U is the measure of uncertainty and k the number of possible outcomes. The convention in information theory is to measure uncertainty in *bits*. Bit is a contraction of binary digit and is either a zero or a one. Because there are 8 possible configurations of 3 bits (000, 001, 010, 011, 100, 101, 110 and 111) 3 digits can encode any integer between 1 and 8, therefore log 8 is 3. All logarithms in information theory are to the base 2, so log 1000 is just under 10 and log 1,000,000 is just under 20. Thus uncertainty is defined by:

[2] $$U = -\log_2 k$$

If we take our roulette example, when the wheel only has one colour and no numbers we are uncertain by $\log_2 1 = 0$ bits of information. If we have two pockets we receive $\log_2 2 = 1$ bit of information, with four pockets 2 bits and with 32 pockets 5 bits of information. Thus any doubling of the number of possible outcomes increases uncertainty with 1 bit.

1.1.3 History of Information Theory

Information theory has its roots in two major fields: that of communication engineering and statistical theory. Communication engineering involved the study of transmission of signals over (technical) channels. In the first half of the 20th century it was thought that an increase in the transmission rate of the information sent would lead to more errors in the transmission. However, a few papers published in the 1920s posed a different view. As discussed by Garner (1962) Nyquist (1924) working for Bell Telephone Laboratories published a paper on factors affecting telegraph speed. He discussed the efficiency of the transmission of “intelligence” and noted that rather than just speed, efficiency was related to the logarithm of the number of possible current levels, i.e. the number of possible alternatives. Hartley (1928) further explored this theory and replaced transmission of “intelligence” by the transmission of “information” and suggested that to measure information one needed a logarithmic measure of the number of alternative possible sequences.

In 1948 Shannon published his seminal two-part paper “A mathematical Theory of Communication”. Building on Nyquist and Hartley’s ideas Shannon and later Shannon & Weaver (1949) suggested that it is not the transmission rate of the information that predicts the number of errors, but the complexity of the encoded information. This complexity is based on a statistical measure of probability, so that each message has a stated probability of occurrence, or a certain “uncertainty”. Shannon named the complexity level entropy (H) and suggested a model to calculate the entropy level of a message.

1.1.4 Shannon’s Information Theory

As discussed above the uncertainty of an event is the logarithm of the number of possible outcomes the event can have. The formula suggested assumes that all of the outcomes of the event are equally likely. This may be the case for a roulette wheel, but for most situations the possible outcomes are not equally distributed. All words do not occur equally often; neither do the letters in the alphabet. Shannon’s work provided answers to this problem of unequal distribution. He suggested the concept of average information. Before we can establish the average information we need to determine the uncertainty of individual elements in a set in the case of unequal probability of those elements within that set. This can be done as follows:

[3] $$U(x) = \log\left[{}^{1}\!/_{p(x)} \right] = -\log p(x)$$

where p(x) is the probability of occurrence of any one category of x.

For example if we were to imagine a roulette wheel (x) with 4 pockets: A, B, C and D. When the pockets are of equal size, the probability of each is equal: 0.25. U(A) is then the same as U(B) U(C) etc. All four elements of x have an information value of – log .25 = 2.

However, if the 4 pockets are not equally distributed, the probabilities for A, B, C and D are different. U(A) will then also be different from U(B), U(C) etc.

Outcome	p	U=- log p
A	0.250	2
B	0.250	2
C	0.250	2
D	0.250	2

Outcome	p	U= - log p
A	0.500	1
B	0.250	2
C	0.125	3
D	0.125	3

Table 1. Probabilities and information of a wheel with equal size pockets *x* (left) and unequal pocket sizes *y* (right).

So when the ball is spun and falls into section B the "surprise" will be smaller than when it falls into C or D, but greater than when it falls into A.

If we were to then spin the wheels numerous times we can calculate the average information by taking into account each elements information in combination with its relative frequency. This is Shannon's measure of average information, or absolute *entropy* of a set:

[4] $$H(x) = -\sum p(x) \log p(x)$$

For wheel *x* the average information is

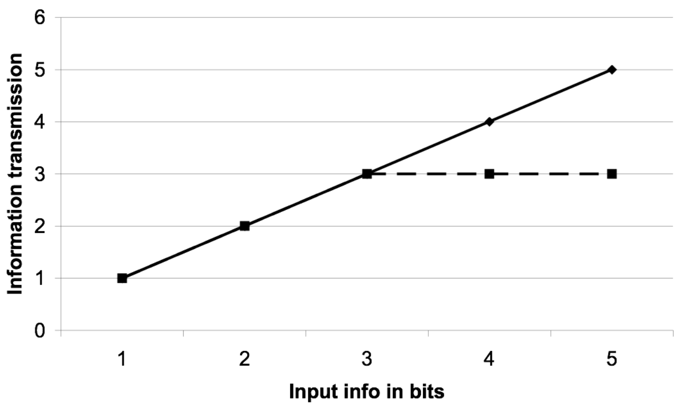
H(x) = -∑ 0.25x2 + 0.25x2 + 0.25x2 + 0.25x2 = 2 bits.

For wheel *y* the average information is

H(y) = -∑ 0.5x1 + 0.25x2 + 0.125x3 + 0.125x3 = 1.75 bits.

Importantly, the entropy of a set is at its maximum value when all the elements in the set have equal probability. When the elements in a set have unequal probabilities of occurring, the relative entropy will be lower, as we saw in the previous examples. The higher the difference in probability, the lower the entropy value.

There is one further notion in Shannon's theory that is important for our purposes and that is *channel capacity*. In communication engineering it was not only important to calculate the information of a message, but also to know how much information a machine could transmit. In order to calculate the channel capacity, varying amounts of input information need to be presented to the machine to determine the maximum information transmission, or channel capacity. So long as the ability of the machine to decode the input information exceeds the stimulus uncertainty, the output information increases linearly with the increase in input information (machine A). However, once the input information exceeds the capacity of the machine, the information transmission will stay constant (machine B).



Graph 1. Example of relation between input information and information transmission for machine A (solid line) and machine B (dotted line).

The channel capacity of a machine (or human being) is the maximum amount of information, or entropy of a set that the machine can process per unit of time.

[5] $$C = {I_{\max}}/{t}$$

Error free transmission of messages or information is only possible as long as the entropy level of the message does not exceed the channel capacity. So in our example machine B will not be able to transmit message error free when the entropy of those messages exceeds 3 bits.

Several studies in the 1950s explored the channel capacity of sensory discrimination in humans. Pollack (1952) for example looked at the discrimination of absolute pitch. He had participants listen to sounds with varying pitch divided into four to twenty categories. He found that once the number of stimulus categories exceeded four to five, information transmission became constant; people were not able to discriminate between the finer pitch differences. This maximum transmission value or channel capacity corresponded to 2.3 bits. Garner (1952) found similar results for the discrimination of absolute pitch.

1.1.5 Applying Information Theory to Language Processing

After Shannon's seminal paper information theory has had myriad applications in psychology, biology, and language sciences. As discussed by Ferrer i Cancho (2010) in psycholinguistics it has been applied amongst other things for measuring the cognitive cost of processing words (McDonald & Shillcock, 2001); inflectional paradigms (Moscoso del Prado Martín, 2004); and the whole lexicon (Ferrer i Cancho, 2006). These papers assume that lexical units that have a higher information load are more costly to access in long-term memory. Probabilities of the lexical items are estimated by frequency; higher frequency words have higher probabilities and therefore lower information loads whilst low frequency words have low probability and therefore high information load. In addition to frequency measures, these papers also take linguistic information such as paradigmatic structure into account when calculating probabilities and information load of lexical items. A detailed description of this work will be provided in later chapters.

1.2 Aphasia

Aphasia is a language disorder that is the result of focal brain damage, most often caused by a cerebral vascular accident (CVA) or traumatic brain injury. In the Netherlands on average 40.000 people suffer a stroke every year. 20% of them develop aphasia. Aphasia affects production and perception of language in both written and spoken modality. The type and extent of difficulties varies greatly amongst patients, but some level of word finding difficulties is evident in all speakers with aphasia. The scientific interest in aphasia is twofold: on the one hand there is a much research on diagnosis, prognosis, assessment and treatment of people with aphasia. The main purpose of this research is to improve our understanding, diagnosis and treatment of people with aphasia and is thus clinically motivated. On the other hand aphasia provides us with a unique window of opportunity to study our language faculty. By far most of the research has used aphasia to gain a better understanding of the structure of language, of the relationship between language abilities and the brain and linguistic theory and is therefore theoretically motivated. This thesis falls into the latter category, although it does have some important clinical implications, which are discussed in the final chapter.

1.2.1 Verbs in Aphasia

People with aphasia often show difficulties in retrieving words from certain grammatical classes. The pattern of relative impairment and sparing varies and is most obvious in a comparison of production of words from the content class (e.g. nouns, verbs and adjectives) and function words (e.g. pronouns, prepositions and determiners). There is a growing consensus that within the class of content words many patients have particular difficulties with verb production. Regardless of the type or severity of aphasia, retrieval of verbs is problematic for the majority of aphasic patients. Where verbs are produced, they are often uninflected (Faroqi-Shah & Thompson, 2007; Zuckerman et al., 2001).

It is not the goal of this thesis to provide a theory on why verbs are particularly difficult for people with aphasia (although I will provide some speculation in the concluding chapter of this thesis). Verbs were chosen for the experimental setup because we know they are difficult to retrieve for people with aphasia. Any performance differences between the people with aphasia and the healthy participants were therefore expected to show up more strongly in a task using verbs. More details on which verbs were used and why will be presented in chapters 2 and 3. A detailed description of inclusion criteria and ethical issues with regards to patient selection will be given at the end of this chapter.

1.3 Specific Language Impairment

Although the majority of this thesis focuses on linguistic performance of aphasic individuals, chapter 6 will investigate reduced processing of children with a *developmental* language disorder. Specific Language Impairment (SLI) is a primary language disorder (Law et al., 1998), which means that affected children fail to acquire language in the fast and easy way that typically developing children do, despite having intact general cognitive abilities. Diagnosis of SLI is primarily based on this discrepancy criterion, first suggested by Stark & Tallal (1981). The ICD-10 (WHO, 1993) criteria for example specify that language skills be at least one SD below non-verbal IQ. The incidence of SLI in kindergarten has been estimated to be 7% (Tomblin et al., 1997) and in specialised class units up to 13% (Archibald & Gathercole, 2006). It has further been shown that many children with SLI continue to have problems in both oral language and written language later in life (e.g. Beitchman et al., 1996).

Children with SLI have been shown to acquire their first words later than typically developing children. Trauner et al. (1995) reported an average age of first words of 23 months, a year later than the average of 11 months for typically developing children. However, there is considerable variability in the acquisition of the first words for all children (Pine, 1995) and there is no qualitative difference between the types of words that children with SLI and younger typically developing children use (Leonard, 1998). So, as Leonard discusses, it is hard differentiate between children with SLI and the estimated 60% of "late talkers" that catch up.

In school-age children with SLI the most striking lexical problem is their word finding difficulty, indicated by long pauses in the child's speech, frequent circumlocution and use of non-specific words such as "things" and "stuff" (Leonard, 1998). Verbs in particular are difficult for these children; they use fewer verbs, have difficulties learning them (Watkins, Rice & Moltz, 1993), and use a more limited variety of them (Rice & Bode, 1993). Similar to the use of non-specific nouns, these children often use general all-purpose verbs (GAP verbs); such as *do*, *have* and *go*. One of the most consistent findings in studies on children with SLI is their extensive difficulty in the acquisition and use of grammatical morphology. Deficits in inflectional morphology such as deficits in tense and agreement resulting in omission of past tense -ed, 3rd person singular –s, be and do have been reported in numerous studies (e.g. Rice et al., 1995). The children always show errors of omission, where these morphemes are supplied they are generally used correctly, a pattern similar to that of younger typically developing children. However where 5-year-old typically developing children supply these morphemes when required in 90% of the cases or more, SLI children still struggle at the age of 8 (Rice, 2000).

It was beyond the scope of this PhD project to investigate the word finding difficulties in verbs for children with SLI. Chapter 6 does however report on an information theoretic approach to the omission of articles in the speech of Dutch children with SLI. The results reported are promising and it would be interesting to explore further word finding difficulties, especially for (inflected) verbs in SLI, within an information theoretic framework in the future.

1.4 Information Theory and Language Disorders

So far I have provided an introduction to the main concepts of information theory and given some background on the two groups of language impaired individuals that will be the focus of investigation in this thesis. Combining the abundant literature and knowledge of lexical processing in aphasia and to a lesser degree SLI with the mathematical notions of "information load", "entropy" and "reducing uncertainty" of information theory proved to be the main challenge of this thesis. Intuitively it makes sense that processing of complex information is difficult for language-impaired individuals. In aphasia one of the most successful ways in assisting word retrieval or sentence production is by limiting the number of possible output words or sentences for the aphasic speaker. Providing a phonological or orthographic cue in naming (cf. Herbert et al., 2001), a limited number of possible target words for a particular picture, or a specific syntactic frame for sentence production (Raymer & Kohen, 2006) all (drastically) improve performance of aphasic speakers. If people with aphasia are given a head start and their number of possible output options is reduced, the task becomes easier. In other words, if the *uncertainty* of the outcome is reduced, aphasic speech is aided. As information theory revolves around resolving uncertainty, using it as a framework for language processing and in particular disordered language processing is not as far-fetched an idea as the reader may have felt it was, upon reading the initial introduction on information theory in this chapter. Having said this, up to this point there have been very few attempts to combine information theory and language disorders. Ferrer i Cancho (2006); Piotrowski, Pashkovskii & Piotrowski, (1995) and Piotrowski & Spivak (2007) use information theory and variations in Zipf's law (a power law natural language follows) to investigate language processing in young typically developing children, children with Down's syndrome and individuals with schizophrenia. A more detailed discussion of this very specific application of information theory will be provided in chapter 5. Aside from these few papers, there is a dearth of studies in the literature on language-processing difficulties within an information theoretic framework. This thesis will aim to provide the first results that show information theory provides an interesting and solid framework to investigate processing of (linguistic) information in language-disordered individuals.

A quick heads up to the (sceptical) reader; I do not claim information theory is the key in aphasia research, nor does the use of these information theoretic tools imply that I think the mental lexicon is organized in terms of optimally coded bit streams. I will remain agnostic about how linguistic structure is implemented in the brain, as the type of experiments used in this thesis do not provide us with information on neural correlates. I do however believe information theory offers the right tools for studying the processing consequences of (paradigmatic) relations in the lexicon. And that it therefore could provide a small step towards a better understanding of what happens in the lexicon of language impaired individuals.

1.5 Research Questions

The three main research questions of this thesis are:

1. To what extent can limitation of information processing capacity as measured within an information theoretic paradigm explain apparent agrammatic behaviour in Dutch people with aphasia?
2. Is the above limitation language - specific or it is observable in other cognitive domains, specifically visual cognition?

3. To what extent can limitation of information processing capacity as measured within an information theoretic paradigm explain the article retrieval difficulties of Dutch children with Specific Language Impairment?

Research question 1 will focus on grammatical morphology and explore the use of articles and verbs (inflectional morphology in particular) in aphasia and will be discussed in chapters 2, 3, 5 and 6. Research question 2 will be tested by using a visual search paradigm in an experiment performed by healthy elderly and aphasic individuals and will be discussed in chapter 4. Research question three will be tested and discussed in chapter 6.

1.6 Recruitment and Selection of Participants

A total number of 92 people participated in this research project. Of these 29 were aphasic patients, 33 healthy young students and 30 healthy elderly participants. The students were recruited at the University of Utrecht. Average ages will be presented in chapter 2. An assistant recruited the healthy elderly participants by contacting local choirs. A match of the healthy elderly participants was made to the aphasic participants based on age and level of education, as described in more detail in chapter 3. The aphasic participants were recruited via local rehabilitation– and aphasia centers. Four centers agreed to participate and obtained local medical ethical permission (locale uitvoerbaardheidsverklaring): Revalidatie Centrum de Hoogstraat; afasiecentrum Utrecht; afasiecentrum Tilburg and CVA groep Samen Verder Tilburg. The local speech therapists provided the aphasic patients currently on their caseload with information on this project. 29 Interested patients signed up to participate.

1.6.1 Inclusion and Exclusion Criteria of Aphasic Participants

The Token Test (Graetz et al., 1992) was used to determine the presence of aphasia as this test has been shown to be sufficiently reliable, sensitive and specific in diagnosing the presence of aphasia (Heesbeen, 2001). Spontaneous speech of all participants was judged by two speech and language therapists to investigate fluency and the presence of word finding difficulties. All participants were monolingual, had Dutch as their native language 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 most suffered a unilateral lesion resulting from a cerebrovascular accident. One patient had suffered multiple infarcts and one patient had suffered from meningitis. Their performance did not differ from the other participants in the group and as this study did not set out to find neural correlates for behavioural data it was decided to include these participants. Onset of aphasia was at least 6 months prior to testing for all participants. All participants had normal or corrected to normal vision and no known oculomotor deficits. In addition to the Token Test, two cognitive tasks were administered to assess any cognitive problems that may interfere with performance in the experimental tasks. The Ruff Figural Fluency test (Ruff, Light & Evans, 1987) was conducted to control for non-verbal initiation, planning, and divergent reasoning. The Trail Making Task (Lezak, Howieson & Loring, 2004) was used to ensure participants did not suffer from visual attention and task switching difficulties. Chapter 3 reports on data for 17 patients as fluency was used as an additional inclusion criterion.

1.6.2 Rationale for Exclusion and Inclusion Criteria

As one might have noticed, I have steered clear of dividing aphasic participants into groups, or requiring a specific classification as one of the inclusion criteria.

For decades scientists and clinicians have tried to cluster symptoms in order to classify syndromes of aphasia. The most used classification is the 'classic taxonomy' based on work by 19th century surgeons Pierre Paul Broca (1824-1880), Carl Wernicke (1848-1904) and Ludwig Lichtheim (1845-1928) which distinguished 6 subtypes of aphasia of which Broca's aphasia and Wernicke's aphasia are the most well-known. In the Netherlands the Akense Afasie Test (Graetz et al., 1992) is most widely used to diagnose type of aphasia. This battery consists of several tasks on language production and perception. Scores on these tasks are used to create a profile of strengths and weaknesses based on which a diagnosis of type of aphasia (Broca, Wernicke, etc.) and severity is made. For research purposes the AAT scores are often used to group aphasic patients in diagnostic groups (e.g. Broca vs. Wernicke).

Over the last few decades, there has been a lot of criticism on the use and validity of classification of aphasia in general and on the classic taxonomy in particular. There are huge discrepancies in the literature on the percentages of patients that can be classified. Goodglass (1981) suggests that 50% of patients cannot be classified within one of the six classical syndromes at all, whilst Albert et al. (1981) suggest as much as 70-80% cannot be classified. Dutch research (Prins & Van de Sandt, 1977; Prins 1987) suggests that only 25% of patients have a 'pure' aphasic syndrome. All others have a mixed aphasia. Furthermore, the language abilities of individuals with the same diagnosis can vary greatly, whilst individuals with different syndromes can have overlapping symptoms. In Dutch research the AAT itself has been subject of much criticism. Günther, Hofman & Promes (2009) show that the AAT does not discriminate well between the traditional syndromes.

Classifying and grouping people with aphasia is challenging to say the least. Heterogeneity within subgroups is large whilst there are many similarities between patients in different groups. However, much of the current research on aphasia still adopts the classic taxonomy as a way of selecting participants for research projects. As a result only a small subset of aphasic speakers is included and conclusions drawn from the investigations only hold for a small group of "pure" patients. Generalisation to the population as a whole is difficult. Although well-formulated inclusion and exclusion criteria are crucial for research on patients, one can question the relevance of projects if the majority of speakers is excluded from the onset, as they do not display the 'ideal' language profile.

For this project I have therefore adopted quite lenient exclusion and inclusion criteria. This means we cannot make any claims about neural correlates of the behavioural data and we ran the risk of not finding any significant results, as the group might be too heterogeneous. It does however mean that any result that is found holds for a much larger part of the aphasic population than most current research projects. For clinicians and crucially, for speakers with aphasia more knowledge of the disorder that holds for the *majority* of patients is of far more interest than theoretical research and conclusions that only discuss a small subset of patients.

1.6.3 Post-hoc exclusion of participants

Two patients were excluded from analysis as their performance on the two cognitive task showed additional cognitive difficulties. One patient was excluded, as her score on the Token Test did not confirm the diagnosis of aphasia. One patient was excluded because she had pre-morbid dyslexia. Data from a further two participants were lost due to technical difficulties. The remaining 23 patients all participated in some of the subtasks of this project.

1.7 Medical Ethical Considerations

In accordance with the World Medical Association Declaration of Helsinki (2008) medical ethical approval for the recruitment and participation of aphasic patients was obtained through the Medical Ethical Committee at the Universitair Medisch Centrum Utrecht (METC protocol number 10/011). In addition to a comprehensive research proposal, a detailed explanation of how we considered and justified the ethical and moral basis of these experiments was offered to the METC in order to obtain permission. The research project was registered at the CCMO (de centrale commissie voor mensgebonden onderzoek) as file NL30433.041.10 in name of E. van Ewijk. All participants received an information pack with a description of the experiments and gave their informed consent before taking part.

1.8 Outline of this thesis

The rest of this book is divided into two parts:

Part A: the experimental part. Chapters 2-4. This part describes an auditory lexical decision and a visual search experiment conducted with three groups: healthy young, elderly and aphasic participants. The effects of several information theoretic measures (two of which are new) on lexical retrieval in these three groups will be discussed. In chapter 4 the results of a visual search task will be discussed and related to the auditory lexical decision results.

Part B: spontaneous speech analyses. Chapters 5-6. This part will look at data from both aphasic speakers and children with SLI. The first chapter will discuss a new application of Zipf's law and speaker entropy and will discuss the use of these tools in aphasic speech samples. I will use these tools to show that constrained by their brain limitations aphasic speakers balance communication (unknowingly) towards saving the cost communication as much as possible. The second chapter will explore a third possible way to use information theoretic measures to investigate reduced processing capacity: the Kullback-Leibler divergence between input and output distribution. In this case I investigate article production and show KL divergence can provide an index of the channel capacity and directly compare individuals with aphasia to children with SLI.

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2 AUDITORY LEXICAL DECISION IN HEALTHY YOUNG AND ELDERLY PARTICIPANTS.

The Effect of Information Load and Inflectional Entropy

2.1 Introduction

2.1.1 Retrieving Words from the Lexicon

The storage and retrieval of words in general and verbs in particular has been a topic of interest for many decades. By the standard model, word retrieval for production starts with some form of communicative intent and ends with the execution of a motor program in order to produce sound (Bock & Levelt, 1994; Garrett, 1982; Levelt, 1989). Several sub steps have been distinguished over the years. Most models agree that at least two processes can be differentiated: retrieval of lexical information, which involves the selection of representations that best capture the conceptual and semantic properties of the speaker's intended message (the lemma) and the retrieval of metrical structure, phonemic and phonetic information (the lexeme). In auditory language comprehension the listener starts with a sound, which they have to map onto meaning in order to figure out the speaker's intended message. Neurobiologically, memory traces for words are frequently conceptualised as networks of neurons interconnected via reciprocal links (Alexandrov et al., 2011). Highly frequent words are thought to be associated with more strongly connected circuits than low frequency words. Upon retrieving a word from memory, whether the process is started by the will to communicate an idea, or by hearing a spoken word, activation spreads throughout these networks. Recent neurobiological research suggests that precise patterns of spreading activation specific to phonological or lexico-semantic processing, show that access to phonological, lexical and semantic word features are all early (between 100 and 200ms post-onset) near-simultaneous processes (Pulvermüller, Shtyrov & Hauk, 2009). Competition is a process that occurs at each level and the speaker or listener has to distinguish the target from distracters at astonishing speed. The Neighbourhood Activation Model (Luce & Pisoni, 1998) for example proposes that lexemes in the lexicon are organised in phonological similarity networks. Upon hearing a target word, all words that sound similar are also activated. If there is a large number of similar entries, finding the target word has to proceed by weighing the goodness of fit of several representations to the incoming sound. Similar competition effects have been reported for lexico-semantic information. Lorsbach & Morris (1991) for example found that in the context of a simple picture naming task, pictures that have a low naming agreement produce a higher level of competition for lemma selection than pictures with a high naming agreement.

2.1.2 Verbal Morphology

The way verbal morphology is represented or stored in the mental lexicon has been fiercely debated in both linguistics and psycholinguistics. The debate has mainly focussed on which (parts of) morphologically complex words are stored in the mental lexicon. The combinatorial dual-route model by Pinker (1991) for example assumes that regular words are not stored in our mental lexicon as complete units. Instead, a deterministic rule combines two separately stored morphemes to produce a morphologically complex form (*walk* + *-ed*). Irregular verb forms like *ran* cannot be computed this way and are therefore assumed to be stored in the lexicon as complete forms. One of the first and most widely described phenomena taken to show the presence of memory traces of morphologically complex words in long-term memory is the frequency effect. All other things being equal, familiar words are more readily recognised than rarer forms (Howes & Solomon, 1951; Baayen et al., 2006). Although frequency effects were initially reported for irregular verbs only, and therefore seen as evidence that only these forms are stored as full units in the mental lexicon, Baayen and colleagues (2008b; Milin et al., 2009) showed that frequency effects are widespread and also occur for regular forms.

It is becoming increasingly clear that, contrary to the assumptions of the dual mechanism model and other models positing obligatory decomposition into morphemes, *all* verb forms leave traces in memory as they are used (Hay & Baayen, 2005; Milin et al., 2009). Baayen and colleagues therefore pose that morphological processing is not best captured by the use of deterministic rules, but rather by probabilistic regularities between form and meaning in language.

In this new line of work, Baayen and colleagues assume that (inflected) words are organised into paradigms and classes (cf. Stump, 2001; Blevins, 2003). As will be discussed in detail below, they suggest that speed of processing of a specific word form is not just dependent on its specific probabilistic information such as form frequency, but also depends on the probabilistic information of the family the (verb) form belongs to. Not dissimilar to the connectionist tradition (Bybee, 1985, 1995) word forms within (inflectional) paradigms and classes are connected. Strength and activation of connections and items is determined by probabilistic information. Ease of access of a specific word form then is more difficult when the activation of that particular form is low (i.e. if the frequency is very low) but also if there is more uncertainty about which candidate to choose from within a particular inflectional family. Baayen and colleagues use concepts from information theory (Shannon, 1948) to link these measures of probability and uncertainty to processing cost and demonstrate that the amount of information carried by an item is negatively correlated with the probability of that event, and positively correlated with processing costs. In other words, the cost of retrieving lexical information from long-term memory is proportional to the amount of information retrieved: the more information retrieved (or the greater the uncertainty about the target item), the higher the processing cost.

2.2 Research Questions Chapter 2

This chapter aims to further develop and investigate probabilistic measures based on information theory to understand the processing of Dutch verbal morphology and specifically the role of inflectional family. A new measure for information load of individual words will be proposed and Baayen's inflectional family measure will be adjusted, incorporating both linguistic characteristics of the verb form and probabilistic information. To further examine the relation between information and processing cost I will look at the effect of inflectional family on reaction times of both young and healthy elderly participants to see if this factor changes with age (cf. if elderly participants need more time to process information). To my knowledge investigating the effect of age on information processing of inflectional morphology has not been done before.

The main questions of the current chapter are therefore:

1. What is the effect of information load of individual lexemes on lexical processing?

2. What is the effect of the inflectional paradigm as a function of not just frequency but also the number of linguistic functions each member has in that paradigm on lexical processing?

3. Does the effect of these factors change with age?

In section 2.3 I will first describe recent work on information theory and (verbal) morphology and explain the various measures. I will then turn to lexical retrieval in the aging brain to review what is already known about the phenomena of cognitive aging and the possible interference with word recognition and retrieval. In section 2.5 I describe the setup of the experiment and provide detailed descriptions of the new information measures. Sections 2.7 and 2.8 discuss the results and implications of our findings.

2.3 Morphology and Information Theory

2.3.1 Inflectional Classes and Information Theory

Recent attempts to quantify the information of a word's paradigm and measure its effect on processing in speech production and comprehension have provided interesting results. The bulk of this research has focussed on nouns, although, as will be discussed later, some research on verbs has been done. One of the first series of papers published to this effect was by Kostiç and colleagues (Kostiç, 1995; Kostiç & Katz, 1987). Using an information theoretical framework Kostiç investigated token and type based counts for inflectional processing of Serbian nouns.

Serbian is a highly inflected language and each noun is characterised by an inflectional suffix that specifies grammatical gender, grammatical number and case. There are however several homophones, e.g. the exponent -a can be used for nominative singular as well as genitive plural and the exponent -e for genitive singular, nominative plural and accusative plural. In addition, each Serbian case encompasses a number of functions and meanings. The nominative case for example can take a subject or predicate role in a sentence context (Kostiç, 1995). Kostiç posed that an increase in form frequency of an inflected noun leads to faster processing, whilst an increase in the number of functions and meanings leads to a decrease, as this can be seen as an increase in form complexity.

Kostiç used an information theoretical approach to obtain a complexity measure of the inflected forms. As discussed in chapter 1, the complexity of an item is based on its probability of occurrence. This probability is then transformed by the (base two) logarithm to obtain the information load in bits as shown in (1)

[1] $$I_x = -\log_2 p(x)$$

in which *I* is the amount of information in bits and *p* the probability of the item occurring.

Kostiç and colleagues used the frequency count of exponents of Serbian nouns as a starting point to calculate the amount of information carried by an inflectional exponent:

[2] $$I_e = -\log_2 \mathrm{Pr}_p(e)$$

where Pr_p is the probability of an inflected variant w_e of lexeme w occurring. This probability was estimated by dividing the frequency of the inflected variant (taken from a two-million word corpus of written Serbian) by the sum of the frequencies of all the distinct inflected variants of this lemma.

As discussed above, exponents in Serbian are not equal with respect to their functional load. Some exponents express more grammatical functions than others. Kostiç proposed to weigh the probabilities for their functions and meanings. By dividing the relative frequency of an inflected form by the number of its functions and meanings one obtains the average frequency per syntactic function/meaning for a given inflected form. In order to obtain the amount of information carried by an inflected form, this average probability should be expressed as a proportion relative to the sum of average probabilities per syntactic function/meaning for other inflected forms of a given paradigm. By averaging over all forms with a given exponent, one can calculate the amount of information in bits for each exponent. Let R_e denote the number of functions and meanings carried by exponent e and F the frequency of that exponent. Then the weighted amount of information I_e can be expressed as follows:

[3] $$I_e = -\log_2\left(\frac{F_e/R_e}{\sum_e F_e/R_e}\right)$$

The obtained value provides a measure for the complexity of each exponent: the higher the information, the higher the complexity of that form. This way the fact that inflected words contain encapsulated syntactic information is taken into account. Kostiç calculated the information load of each inflectional class for Serbian feminine nouns. Table (1) provides the frequency, number of functions and meanings and amount of information carried by the exponents for Serbian feminine nouns.

Exponent	Case & number	Frequency	R	Information
a	Nom sg/ gen pl	12.06	54	1.464
u	Acc sg	5.48	58	2.705
e	Gen sg/nom pl/acc pl	14.20	112	2.280
i	Dat sg/ loc sg	3.80	43	2.803
om	Ins sg	1.94	32	3.346
ama	Dat pl/ loc pl/ins pl	1.69	75	4.773

Table 1. Case & number, frequency, number of functions and meanings (R) and information load of the exponents for Serbian feminine nouns. Adopted with permission from Kuperman (2008).

In a series of visual lexical decision experiments using a number of Serbian nouns, Kostiç and colleagues showed that mean latencies had a strong positive correlation with information load. In other words exponents carrying a greater average amount of information are harder to process. Kostiç thus provided us with a quantitative measure for inflected words based on frequency as well as syntactic information and showed that this measure was an excellent predictor for the cognitive cost necessary to process these words.

2.3.2 Individual Lexemes

The probabilities that were used in Kostiç' first work were estimated by summing across all words with a given exponent (e.g. –a,) in a given inflectional class. This means that the information on individual paradigms of specific words is lost. The effect of word-specific probabilities of exponents has been very little researched. In 2003 Kostiç and colleagues applied the information load measure to individual lexemes, thus providing lexeme-specific information. They then chose lexemes with the highest and lowest I values to construct two sets and calculated the average I for each exponent in both sets. Latencies in a visual lexical decision experiment showed a positive correlation to information load. The effect of group (high vs low information) was independent of the general class-based information values, indicating that individual probability distributions of a specific lexeme have an important effect on processing.

2.3.3 Inflectional Paradigms

In a related strand a series of experiments was performed gauging the role of information in morphological paradigms for compounds (De Jong, Feldman, Schreuder, Patizzo & Baayen, 2002; Kuperman, Bertram & Baayen, 2008) and derivational and inflectional paradigms (Baayen, Feldman & Schreuder, 2006; Milin Filipovic Durdevic & Moscoso del Prado Martín, 2009). One of the measures developed by this group is *inflectional entropy,* which calculates the amount of information carried by a word's inflectional paradigm, in bits. It is estimated as

[4] $$H = -\sum p_i \log p_i$$

with i ranging over the different phonologically distinct inflectional variants of the word, and p_i representing the relative frequency of that inflectional variant in its paradigm. This measure, based on Shannon's (1948) notion of entropy of a set turns out to be relevant for measuring complexity of lexical access. Intuitively, a greater number of members in a paradigm will lead to a greater entropy of the paradigm. However, it also follows from (4) that if the frequencies of the members within the paradigm are very different, the entropy decreases. In a regression analysis of English monomorphemic words Baayen et al. (2006) found that inflectional entropy has a negative correlation with reaction times in a visual lexical decision experiment. Baayen argues that words with a more complex, informationally rich inflectional paradigm have more connections to other words in the mental lexicon, therefore allowing for faster response times during lexical decision. Inflectional entropy is an estimate of the amount of support a word receives from the inflectional paradigm to which it belongs.

In 2004 Moscoso del Prado Martín and colleagues proposed to combine the information load measure and the paradigmatic entropy (of which inflectional entropy is a part) to create a measure which encompasses the combined influence of these two factors, as well as its derivational paradigm; the *information residual*. For their information load measure they did not take the number of syntactic functions and meanings into account, as suggested by Kostiç, as they were unsure how such an estimate should be calculated for derivational forms[1]. In a re-analysis of three previously published studies on monomorphemic words, they show that information residual has a consistent inhibitory effect in all experiments. Furthermore, the information residual analyses significantly outperformed or performed as well as a combination of the more traditional counts (frequency, family size and cumulative frequency). Subsequent work (Baayen et al., 2006; Milin et al., 2009) however suggests that inflectional entropy, frequency and information load do have independent effects on (the speed of) lexical retrieval.

In summary, previous work on lexical retrieval using an information theoretic framework has focussed on the effect on processing of *inflectional classes* and *inflectional paradigms*. Work by Kostiç provided us with a measure of information load of global classes. This work showed that exponents carrying a greater

[1] In my calculations I do include the number of functions/meanings to calculate inflectional entropy, see 2.5.4 calculation of independent variables.

average amount of information are more difficult to process. For Serbian masculine nouns for example forms with the exponent –u (information load 5.744 bits) takes longer to process than the exponent –i (information load 2.381 bits) (Milin et al., 2009). Research on inflectional paradigms provided us with a measure of paradigmatic complexity gauged by the entropy measure *H*. H has been applied to derivational and inflectional paradigms and was shown to affect processing latencies.

2.3.4 Information Theory and Verbal Inflection

Although the roles of inflectional classes and paradigms have been well documented for nouns, verbs have only recently gained attention. In several papers Tabak et al. (2006; 2010) showed effects of the paradigmatic structure in the processing of Dutch verbs. In a visual lexical decision experiment looking at present and past tense verbs they found a facilitatory effect for both frequency and inflectional entropy for regular and irregular verbs. Importantly, the measures did not correlate, showing that both have independent effects on processing latencies. In a naming task inflectional entropy had an inhibitory effect on both regulars and irregulars, i.e. verb forms with high inflectional entropy values had longer reaction times than verb forms with low inflectional entropy values. As this effect was modulated by measures of phonological neighbourhood density the authors suggest that the inflectional entropy effect reflects the process of lexical competition within paradigms. In an informationally rich paradigm it is more difficult to select the target form from its neighbours. Similar findings were reported by Baayen & Moscoso del Prado (2005) on English verbs. In a naming task latencies increased with increasing inflectional entropy, whereas in lexical decision the effect was facilitatory. The authors suggest that "in general, a greater entropy, i.e., a greater information load of the inflectional paradigm, provides a source of evidence in lexical decision that an item is indeed a word, and likewise makes a word feel more familiar" (2005:34). I will provide an explanation of why the effect of inflectional entropy has opposing directions in language comprehension and production in the discussion of this chapter.

In this chapter I focus on Dutch verbs to further investigate the role of the complexity of inflectional paradigms on lexical processing cost. I adapt Kostiç et al.'s original information load measure for classes of Dutch verbs. Similar to Kostiç (2003), I investigate effects for lexemes, rather than those of global classes. Unlike Kostiç, however, I will not construct groups of high versus low information load, but instead, I will show that it is actually possible to look at the effect of information load on retrieval of individual lexemes.

Furthermore, in order to move away from a mere frequency effect, I further develop Baayen's inflectional entropy measure. Rather than calculating the entropy of the inflectional paradigm based on frequency, I propose to incorporate linguistic characteristics of the verb form. In line with Kostiç I will gauge the linguistic information by calculating the number of functions and meanings a specific verb form has. I conjecture that the strength of the memory traces of verb forms are not just determined by a general frequency effect (i.e. the more often an item gets retrieved, the easier it will be to access) but that it is the combination of linguistic characteristics and frequency that determine ease of retrieval. In other words, it is not just how often you hear a verb form that determines strength of the memory trace, but how often on average different grammatical operations are performed with that specific verb form. Information theory provides us with a tool to investigate processing cost of both individual items and a word's paradigmatic family. The cost of retrieving lexical information from long-term memory is proportional to the amount of information retrieved: the more information retrieved, the higher the processing cost. This raises the question if the effect of information load is different in groups that are known to have reduced processing capacity. A first step towards understanding the role of information and paradigmatic complexity in lexical access in populations with reduced processing capacity is to investigate what happens in healthy elderly participants.

2.4 Lexical Retrieval in the Aging Brain

Several studies on memory and language in elderly have made use of the theoretical notion of spreading activation. Upon retrieval of an item, activation spreads to the network associated with that item. Howard, Shaw & Heisley (1986) suggest that there may be age-related changes in spreading activation. In a lexical decision experiment using semantic priming they showed that elderly participants had slower priming onsets and argue that this may be the result of a slowing of semantic activation with age. Similar findings have been reported by LaGrone & Spieler (2006). They found frequency to be a significant factor in naming for both young and elderly participants. There were marginal age differences with the elderly having a stronger frequency effect than the young participants. The authors conclude that lexical competition has a strong influence on retrieval and that the process of resolving this competition is particularly age sensitive.

Balota et al. (1988) however found no evidence for slowed lexical retrieval. In a semantic priming task they found that semantic relatedness and strength of the relationship of the prime and target affected pronounciation latencies of the target word similarly for young and elderly participants. The authors therefore conclude that the basic retrieval mechanism of spreading activation is not affected by age. Federmeier et al. (2003) recorded ERPs as young and elderly participants listened to sentences that contained different types of context information: lexical, sentential, both, or neither. Their results show age-related changes in language processing at the level of construction of message-level meaning, but not the lower level sensory analysis or lexical retrieval.

It is thus still unclear if and how spreading activation and lexical retrieval slows down or changes with age. Furthermore, previous experiments focussed on semantic connections. The effect of age on activation of (inflectional) paradigmatic and its effect on lexical retrieval has (to my knowledge) not yet been investigated.

2.5 Materials and Method

2.5.1 Participants

Two groups of healthy young adults and two groups of healthy elderly participants participated in this experiment. Each group consisted of 11 participants. The young adults were students and recruited at Utrecht University. An assistant recruited the elderly participants via local choirs. All participants had normal levels of hearing, were right-handed and were monolingual native speakers of Dutch. Each participant received 5 euros for their participation. Average age for the two student groups was 22.4yrs (SD 4.6) and 25.1 (SD 7.5). Mean age for the elderly groups were 62yrs (SD 9.1yrs) and 70yrs (SD 9.8yrs). Although there was a small difference in age for the two elderly groups this is unlikely to affect the results as there is no between group comparison for these two groups.

2.5.2 Stimulus materials

The verbs used in this study were adopted from Tabak (2010). 286 simplex verbs were used; 143 regular and 143 irregular verbs. Lemma frequencies were matched for regular and irregular verbs. For practical reasons only singular & plural past tense forms and infinitives were used. From these two lists were created: an infinitive list and a past tense list. The infinitive was chosen as it is arguably the most neutral form of the verb in Dutch. Past tense was chosen as it is the form in which the difference between regulars and irregulars is evident. For each list 286 phonotactically legal pseudoverbs were pair wise matched to the real verbs. The pseudoverbs had the same distribution of first phoneme, had a CV-structure, and had the same number of syllables as the verb form they were matched to. The two lists therefore consisted of 286 real verbs and 286 pseudoverbs. Both lists were then spoken in isolation by a female native speaker of standard Dutch with a clear speaking style. In addition, 6 practice items (3 verbs that were not part of the list and 3 pseudoverbs) were recorded to familiarize the participants with the speaker's voice and with the task of lexical decision. The materials were recorded on digital audiotape with a Sennheiser microphone. They were fed as digital input into the computer, and down sampled to 32 kHz. Each word was cut and stored as a separate sound file using PRAAT (www.fon.hum.uva.nl/praat/).

2.5.3 Procedure

The software package FEP (http://www.hum.uu.nl/uilots/lab/resources.php) was used to create an experimental script to control stimulus presentation and acquire data. This experimental script automatically randomised the order of presentation of the verbs and pseudo verbs. Each group was exposed to only one list so that the infinitive list was presented to a group of young and a group of elderly participants and the past tense list was presented to a different group of young and elderly participants.[2] Each participant was confronted with 1 list. In other words, participants either heard past tense, or infinitive verbs. Participants were seated at a table, wearing closed earphones. They were asked to indicate whether a presented word was a real word or a non-word by pressing one of two buttons labelled YES and NO on a button box. The auditory stimuli were presented at a comfortable loudness level. Each stimulus was preceded by a beep and 150msec silence. After each stimulus the participant had 3000 msec to respond. 500msec after the response the next stimulus was presented. If the participant failed to respond within 3000 msec the next stimulus was presented. Participants were asked to use their dominant hand only to press the buttons. Reaction times were measured from target offset until the button press. Accuracy was automatically recorded. During the practice session each participant's performance was monitored in order to ensure they understood the task. After the practice items participants were given the opportunity to ask questions. Participants were told that they could not correct their response once given. The experiment lasted about 45 minutes. Participants were given a short break halfway through the experiment. For 1 participant in the elderly group past tense group data were lost during testing. Analyses for this group were therefore performed for 10 participants.

2.5.4 Calculation of Independent Variables

As described in the introduction, several independent variables were created:

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[2] The decision to use this design, rather than a 2x2 design was statistically motivated. As I use a large number of independent factors *and* these factors have a large number of items that are individually correlated to reaction times, providing each participant with both lists would lead to the necessity of a very complicated cluttered analysis (van den Bergh, personal communication).

Lemma frequency[3]*:* the summed frequencies of all inflectional variants of each verb were extracted from CELEX (Baayen, Piepenbrock & Gulikers, 1995)

Form frequency: form frequencies were extracted from CELEX.

Synsets: As described by Tabak et al. (2009) the number of synsets, or synonym set, was calculated for each verb, using EuroWordNet (Vossen, Bloksma, & Boersma, 1999). In wordnet a synset represents one underlying lexical concept. A synset can consist of one single word, or multiple (complex) words. One word can occur in several synsets. In other words the number of synsets of one verb comprises the number of different lexical concepts that verb can represent. An example of the synsets of lopen (walk) is presented in table 2.

1.	doorgaan (go on), aanhouden (keep on), continueren (continue), doorlopen (pass through), lopen (walk), voortduren (continue)
2.	draaien (turn), lopen (walk)
3.	leiden (lead), lopen (walk), lopend voeren (lead along)
4.	lopen (walk), gaan (go), treden (tread)
5.	verlopen (elapse), gaan (go), lopen (walk), marcheren (march)
6.	vloeien (flow), lopen (walk)
7.	volgen (follow), doorlopen (keep on walking), lopen (walk)
8.	zitten (sit), liggen (lie), lopen (walk), staan (stand)

Table 2. The synsets of lopen, 'walk', in the Dutch EuroWordNet. Adopted with permission from Tabak (2010)

This variable is not part of information theoretic framework, but has been added to the analyses as a semantic measure, in order to investigate if the structure of the lexicon changes with age (and perhaps more plausibly in language disordered individuals, cf. chapter 3). It provides an estimation of the density of the semantic network of the verb.

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[3] Data on lemma frequency, form frequency and number of synsets were kindly supplied by Wieke Tabak, MPI Nijmegen, the Netherlands.

Information load

The original measure of information load as described by Kostiç (2003) was used to calculate the information load of each individual verb form. Form frequency for each inflected verb in a paradigm was extracted from CELEX. In order to gauge the number of functions of a specific verb form the number of grammatical functions that specific form can fulfil in Dutch was calculated (see table 2) Information load was then calculated with the formula described in [3] which is repeated below:

[3] $$I_e = -\log_2\left(\frac{F_e/R_e}{\sum_e F_e/R_e}\right)$$

in which I equals information load of verb form (e), F the frequency of the verb form and R the number of grammatical functions the verb form can fulfil. Unlike previous work, information load was not averaged for a given exponent, but rather information load of individual verb forms were calculated, as shown in table (3).

Verb form	**Form freq**	**Pr**	**R**	**Pr/R**	**I**
Speel	301	0.019	2 (1st & 2nd pres sg)	0.001	6.66
Speelt	2866	0.182	2 (2nd & 3rd pres sg)	0.091	3.45
Spelen	7028	0.447	4 (1st, 2nd, 3rd pl & inf)	0.111	3.15
Speelde	2732	0.174	3 (1st, 2nd, 3rd past sg)	0.058	4.10
Speelden	893	0.056	3 (1st, 2nd, 3rd past pl)	0.019	5.72
Gespeeld	1870	0.119	1 (past participle)	0.119	3.07

Table 3. Frequency, number of functions and information load for the inflected forms of the verb *spelen* (to play)

Inflectional family size: entropy (H)

This measure has been suggested to capture the amount of information carried by a word's inflectional family. Inflectional entropy as described in Kostiç, Markovic, & Baucal (2003) was adopted in the following manner: frequency for each verb form in a paradigm was extracted from CELEX. For each verb form the number of grammatical functions that specific form can fulfil in Dutch was calculated. F/R was then calculated for each inflected form of a given verb. This value (rather than probability of occurrence only) was used to calculate the inflectional entropy for each verb.

[4] $$H = -\sum p \log p$$

in which *p* equals [5]

[5] $$p = \frac{F_e / R_e}{\sum F_e / R_e}$$

in which F_e represents the probability of a verb form within its inflectional paradigm and R the number of functions that verb form can fulfil. This measure captures the relative probability distribution of all inflected verb forms of a particular lemma. If the frequencies of the members within the paradigm are very different, the entropy decreases. In other words, inflectional entropy is a measure of distinguishability within an inflectional family. It captures how similar or different the probability distribution of an inflectional paradigm for one lemma is. Entropy for the inflectional paradigm of *spelen* (to play) for example is 1.44. The probability distribution of the inflectional forms of the verb *scheppen* (to ladle) is more diverse than for *spelen* and as a result the entropy of the inflectional family is lower (1.20). A visual representation of the two inflectional paradigms is presented in graph (1). Each part of the pie chart represents f/r for one inflectional form of the verb (e.g. *speelt*).

Figure 1. Pie chart representation of the inflectional paradigms of *spelen* (left) and *scheppen* (right). The probability distribution is more equal for *spelen* which leads to a larger entropy value.

2.6 Results

Reaction times and error rates were measured for all participants. For the past tense list for both groups 1.5% of data were missing, no button was pressed within the allotted time. For the infinitive list 1.3% of data were missing for the elderly and 0.9% for the young group. All individual data points were included and the required significance level for all statistical tests was set at .05 unless otherwise stated. Reaction times and error rates for both lists and all groups are reported in table 4. The analysis of reaction times includes both correct and incorrect responses.

	Infinitives		**Past tense**	
	Mean RT	*Correct %*	*Mean RT*	*Correct %*
Young	764 (*SD* 366)	94.4%	709 (*SD* 385)	91.1%
Elderly	628 (*SD* 321)	95.6%	798 (*SD* 400)	94.1%

Table 4. Mean reaction time in msec and percentage correct on the auditory lexical decision task for young and elderly participants.

For the infinitive list an independent samples t-test revealed a significant difference in RT for the 2 groups, with the elderly being faster than the young

group $t(6125)=-8.566$, $p<0.01$ and no significant difference in the number of errors. Closer inspection of the error rates for the groups showed that the young participants made significantly more misses than false alarms (repeated measures $F(1,3135)=7.142$ $p<0.05$) whereas the elderly showed no pattern.
For the past tense list an independent samples t-test revealed that there was a significant difference in mean RT ($t(5810)=-8.630$, $p<0.01$) with the young group being faster than the elderly group and a significant effect in the number of errors ($t(5930)=-3.947$, $p<0.01$), with the young group making more mistakes than the elderly. No response bias was found for either group.

The distribution of the latencies was highly skewed. For further analyses this skewness was reduced by means of a logarithmic transformation. Distributions were checked for normality. Correct answers only were used for further analyses. Each list and group was analysed individually to investigate the effect of our information theoretic measures on reaction times. First, correlations between reaction time and individual factors were plotted. A linear mixed model analysis was performed with participant and verb as crossed random effects. All main effects and interactions were investigated. For reasons of space the tables and figures below only report those predictors and interactions that reached significance.

2.6.1 Infinitives

For the *young* group the following significant correlations were found: lemma frequency ($F(1,3001)=26,548$, $p<0.001$); form frequency ($F(1,3001)= 61.717$, $p<0.001$); number of synsets ($F(1,3001)= 24,822$, $p<0.001$); entropy ($F(1,2943)=4,771$, $p<0.05$); and information load ($F(1,2991)= 17,052$, $p<$ 0.001). For the *elderly* group the following significant correlations were found: lemma frequency ($F(1,3001)=26,548$, $p<0.001$); form frequency ($F(1,3001)=$

61.717, *p*<0.001); number of synsets (*F*(1,3001)=24,822, *p*<0.001); and information load (*F*(1,2991)= 17,052, *p*< 0.001).

Regression graphs are presented below for each significant correlation.

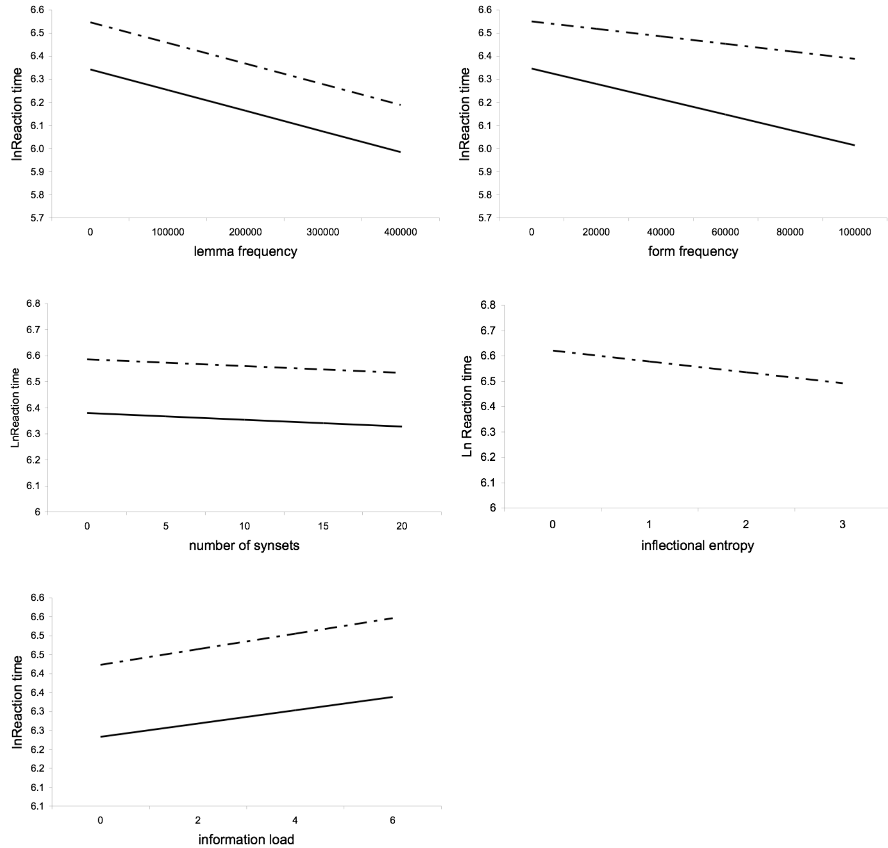

Figure 2. Regression lines for significant correlations between lnRT and independent factors lemma frequency, form frequency, number of synsets inflectional entropy, and information load respectively. Dotted lines represent young participants, solid lines the elderly group. For inflectional entropy there was no correlation with lnRT for the elderly participants.

A linear mixed model analysis was then performed on the data for each group separately with participant and verb as crossed random effects. All main effects and interactions were investigated. The tables below display the estimated coefficients of the predictors in the multilevel model fit to response latencies of the lexical decision experiment.

For the young participants:

	Estimate	**Std error**	***Df***	***t***	**Sig.**
Intercept	6.4883	.1107	68.496	56.581	.000
nSynsets	-.0128	.0046	255.173	-2.772	.006
Info load	.0376	.0146	261.341	2.569	.011

Table 5. Multilevel analyses on the reaction times on the infinitive list of the young participants

For the elderly participants:

	Estimate	**Std error**	***Df***	***t***	**Sig.**
Intercept	6.2853	0.0759	47.277	82.706	.000
nSynsets	-.0121	.0056	273.195	-2.137	.033
Info load	.0359	.0174	273.436	2.061	.040
Form freq	-6.6 E-6	1.78 E-6	272.840	-3.689	.000

Table 6. Multilevel analyses on the reaction times on the infinitive list of the elderly participants

2.6.2 Past tense

For the *young* group significant correlations to response latencies were found for: lemma frequency ($F(1,2858)=8,318$ $p<0.001$); form frequency ($F(1,2858)= 3.994$, $p<0.05$); number of synsets ($F(1,2858)=13.389$, $p<0.001$); entropy ($F(1,2850)=25.340$, $p<0.001$); and information load ($F(1, 2829)= 4.718$ $p< 0.05$).

For the *elderly* group significant correlations to response latencies were found for: number of synsets (F $(1,2644)=17.166$, $p<0.001$); inflectional entropy

(F(1,2635)=14.921, p<0.001); and information load (F(1, 2617)= 4.963 p< 0.05).

Regression graphs are presented below for each significant correlation.

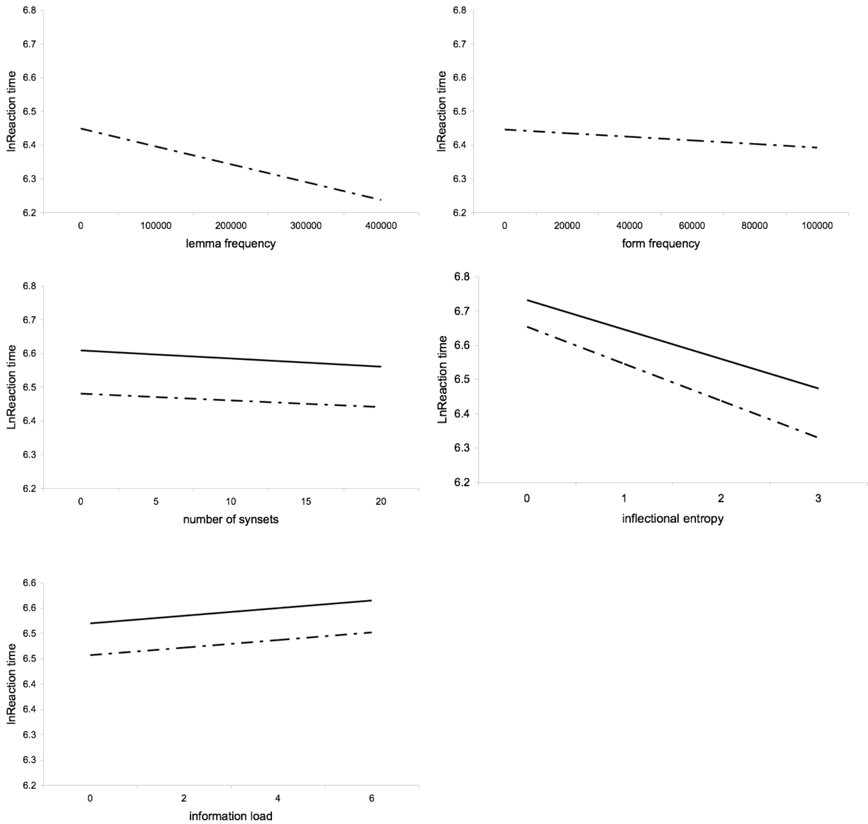

Figure 3: Regression lines for significant correlations between lnReaction times and independent factors lemma frequency, form frequency, number of synsets inflectional entropy, and information load respectively. Dotted lines represent young participants, solid lines the elderly group. For lemma and form frequency there was no correlation with lnRT for the elderly participants

A linear mixed model analysis was then performed for each group with participant and verb as crossed random effects. All main effects and interactions were investigated. The tables below display the estimated coefficients of the predictors in the multilevel model fit to response latencies of the lexical decision experiment.

For the young participants:

	Estimate	**Std error**	*Df*	*t*	**Sig.**
Intercept	6.7665	.0986	32.642	68.584	.000
Regularity	-.1166	.0247	276.960	-4.720	.000
nSynsets	-.0101	.0043	268.539	-2.332	.020
Infl entropy	-.1069	.0318	277.676	-3.362	.001
Lemma Freq	-6.237 E-7	2.86 E-7	263.984	-2.179	.03

Table 7. Multilevel analyses on the reaction times on the past tense list of the young participants

For the elderly participants:

	Estimate	**Std error**	*Df*	*t*	**Sig.**
Intercept	6.8607	.0983	28.167	69.726	.000
Regularity	-.1384	.0240	278.846	-5.748	.000
Infl entropy	-.0869	.0042	275.484	-3.443	.001
nSynsets	-.0146	.0312	276.093	-2.784	.006

Table 8. Multilevel analyses on the reaction times on the past tense list of the elderly participants

Finally the results of the young and elderly group were combined for the past tense and for the infinitives to investigate possible interactions between group and other factors. No significant interactions were found between group and the independent variables in the multilevel analyses.

2.7 Discussion

The current chapter aimed to further investigate the role of information load of individual lexemes and inflectional entropy in the processing of Dutch verbs. To look at the possible effect of age on these measures, two groups were included: a group of healthy young and healthy elderly participants. The research questions for this chapter are: (1) What is the effect of information load of individual lexemes on lexical processing? (2) What is the effect of the inflectional paradigm as a function of not just frequency but also the number of functions each member has in that paradigm on lexical processing? (3) Does the effect of these factors change with age?

As discussed in the introduction of this chapter, information theory has been used as a fruitful tool to gauge processing cost of lexical retrieval from long-term memory. Most of the experimental work using notions from information theory has focused on the processing of nouns. Work by Kostiç and colleagues on (Serbian) noun inflection showed that exponents of an inflectional form carrying a greater average amount of information are more difficult to process. Kostiç et al. (2003) found this to be true for inflectional classes of words with a given exponent and for individual word-specific probabilities of inflectional exponents. Research on inflectional paradigms (Milin et al., 2009) provided us with a measure of paradigmatic complexity gauged by the means of entropy measure *H*. H has been applied to derivational and inflectional paradigms and was shown to affect processing latencies. Inflectional entropy for verb paradigms was shown to have a facilitory effect in perception tasks and an inhibitory effect in production tasks.

The results of the auditory lexical decision experiment for each verb form (infinitive and past tense) and each group (young and elderly) will now be discussed, followed by a general discussion of the implications of these findings for lexical retrieval in the (elderly) brain.

Unsurprisingly facilitatory effects were found for most of the participant groups for form frequency and/or lemma frequency. Importantly these findings were present for both irregular and regular verbs, indicating that both are stored in the long-term memory, providing more evidence against decompositional models of inflectional morphology.
Simple correlations further revealed effects for information load and inflectional entropy for almost all groups. Information load had an inhibitory effect indicating that the amount of information carried by a word's inflected variant is positively correlated with latencies. This is in line with previous work on (verbal) morphology (Tabak, 2010) (and see for a similar approach to syntax Levy, 2008). In contrast to previous studies on general class effects, I show that information load of *individual* lexemes affects latencies. As discussed in the introduction, our measure of information load is based on frequency as well as the number of functions and meanings of the specific verb form. Frequency measures were outperformed by information load in the multilevel model, showing that it is the combination of frequency and *linguistic characteristics* that affect latencies. My interpretation of this finding is that the strength of a memory trace in long term memory is thus not determined by how often one hears/uses the verb form but how often on average a verb form is used in a specific grammatical context and that this affects ease of retrieval.

An increase in inflectional entropy was associated with a decrease in reaction time in my lexical decision experiment. Similar findings were reported by Tabak (2010) and Baayen & Moscoso del Prado Martín (2005) in comprehension experiments. In contrast, production experiments (Tabak, 2010; Bien, Baayen

& Levelt, 2011) often reveal an inhibitory effect of inflectional family on latencies. As briefly touched upon by Baayen & Moscoso del Prado in their 2005 paper, the nature of the task determines the direction of the effect of the inflectional paradigm. In order to understand why this is the case, let us reflect on what this measure actually captures. Entropy is determined by the probability distributions of the items in a set. The entropy of a set is at its maximum value when all the elements in the set have equal probability. The higher the differences in probability, the lower the entropy value. The inflectional entropy of a paradigm then is higher if the probability distribution of all members is equal. In a production task the speaker has to select and activate the correct verb form from the lexicon. This action is *conceptually* driven. In other words, one starts with a concept and then selects a corresponding lemma from the lexicon. If the verb form the speaker requires comes from a family of high entropy it will be more difficult to distinguish it from its family members. Thus, in production, the inflectional family entropy effect reflects competition in lexical retrieval. This is observed in production tasks by longer latencies verbs from families with high inflectional entropy.

Unlike word production, lexical decision is *perceptually* driven. Upon hearing the target word, the word form activates the representation stored in long-term memory. Similar to connectionist models such as Cohort (Marslen-Wilson, 1987), I assume activation also spreads to members of the word's (inflectional) paradigm. Unlike the Cohort model, activation spreading is not determined by overlapping phonological information between target and distracters, but based on probabilistic information of the form itself and the probabilistic distribution of the inflectional paradigm the word belongs to. Inflectional paradigms with high entropy have strong short links between the family members within the paradigm as the information distribution between members is near equal. In psychological terms, closeness in probability distribution means more equality among base levels of activation. In high entropy families activation of the family members boosts the activation level of the target, which means it is faster in reaching the threshold for retrieval, leading to shorter response latencies.

Although frequency effects were found when performing simple correlations on the data, they were outperformed by the information theoretic measures in the multilevel model. The results of the multilevel models for infinitives and past tense will now be discussed. For the infinitives information load of the individual lexeme is an important predictor for latencies. In line with Kostiç (2003) there is an inhibitory effect of information load; higher information load leads to longer processing. Although inflectional entropy did significantly correlate with reaction time for the infinitives in a simple correlation, it does not contribute to the multilevel model. I speculate that this is because infinitives are typically the most prominent in the paradigm. Infinitives have been shown to be the easiest verb form for people with different forms of reduced processing capacity (i.e. children (Wexler, 1996), people with aphasia (Bastiaanse & Jonkers, 1998) and it is acquired early in language acquisition (Wexler, 1996). I believe it is therefore the 'hub' of the inflectional paradigm. The prominence of the infinitive in the paradigm allows for less influence of the family as a whole in lexical processing. Further support for this hypothesis comes from having a closer look that the information load data of the inflectional paradigms used in this experiment. Often (though not always), the infinitive form has the lowest information load of the family.

More evidence for this comes from the results of the past tense task. Although the two lists cannot directly be compared as they were presented to two different groups, I find that for past tense inflectional entropy outperforms information load in the multilevel model. Past tense forms, notoriously difficult for people with processing disorders and acquired later in language acquisition are more influenced by the effect of the distribution of the members in the paradigm. More equally distributed, dense inflectional paradigms provide more support to the processing of the past tense form of that paradigm.

Before I turn to discuss the (lack of) difference between the young and elderly groups, there is one further robust factor in all analyses I need to consider: the number of synsets. In all multilevel models the number of synsets of the verb has a facilitatory effect on latencies. In other words, the more synonyms a verb has, the faster the reaction times. The number of synsets is a measure of semantic density (Tabak, 2010); verbs with higher numbers of synsets have greater semantic connectivity. Our results support the view that words with greater semantic density are processed faster. Interestingly, Tabak (2010) only found this effect for irregular verbs, which corresponded to her finding that overall in Dutch irregular verbs, have a greater semantic density than regular verbs. Our data however show an effect for both regulars and irregular verbs. This finding is in line with previous findings (e.g., Bybee & Slobin (1982); Patterson, Lambon Ralph, Hodges, & McClelland (2001)) suggesting that upon recognition of a word with strong (semantic) connectivity the whole (semantic) network of connections resonate, boosting activation of the target word. Our findings suggest that a strict separation of form and meaning in the mental lexicon is a simplification of the true complexity of lexical organisation in the brain.

To investigate word recognition and specifically the role of the aforementioned information theoretic measure on lexical processing in the aging brain, I included two groups of elderly participants in the current study. Overall the elderly participants performed equally well, or better than the young participants. For the past tense verbs I found that the elderly participants were slightly slower than their younger peers, but all the effects that were found for both groups had the same direction and strength in both groups. The frequency measure did not reach significance for the elderly group on the past tense verbs, indicating again that the information theoretic measure offers a more sensitive measure to explore processing cost in lexical processing.

For the infinitives individual information load is an important predictor in processing time for both the young and elderly group. The effect of inflectional entropy did not reach significance in the multilevel model for either group, but for the young group there was a significant correlation between reaction time and inflectional entropy. For the elderly group this correlation was not even present when disregarding all other factors. It thus seems that the effect of family connections when selecting the most prominent candidate of the family is lost for the elderly participants. If this were the case I can predict that properties of the individual verb forms will be more important. And in fact this prediction bears out; for the elderly participants listening to the infinitive verb forms, form frequency is one of the factors in the multilevel model significantly facilitating reaction times. In none of the other groups does this factor reach significance. From our data it is difficult to say whether the faster reaction times are the result of the lack of influence of the family, or whether lexical access for the most prominent infinitive form of the inflectional paradigm was so fast that spreading activation to its family members was not finished by the time the participant had already pressed the button. Why this would be the case for elderly participants but not for their younger peers remains an open question.

There were no interactions between any of the factors and group, indicating that overall the elderly groups performed very similar to their younger peers. Almost all of the factors that affected latencies in the young groups did so for the elderly and the strength and direction for all these factors was the same for both groups. These findings indicate that the effects of inflectional family on the recognition of verbs do not change with age. However, I feel I cannot conclusively argue that there was no age effect as, similar to LaGrone & Spieler (2006) I find marginal differences in the infinitive experiment with the elderly having a strong frequency effect on latencies. LaGrone & Spieler use the difference in frequency effect in addition to a stronger effect of name agreement in elderly participants to argue that resolving competition in lexical retrieval is age sensitive. The authors suggest that age-related changes in the efficiency of inhibitory connections to competitors of a target word could reduce the ability of the more activated target to suppress the activation of competing entries. Lexical competition would therefore be more difficult to resolve. In our study I have provided a measure for calculating this state of "uncertainty" between competitors in an inflectional paradigm. As discussed this measure did not show age related changes. The inflectional paradigm is of course a tiny subset of an item's broader (semantic) network. It could therefore be that these subtle changes in spreading of activation and difficulty in resolving uncertainty are not captured by looking at inflectional paradigms only. It may only become apparent when investigating more distal (semantic) connections (although the results on the effect of number of synsets do not support this hypothesis). Furthermore, recent imaging studies (e.g. Whiting et al., 2003) show that subtle age related changes in lexical retrieval might not be captured by behavioural experiments, but do show up during imaging. It would therefore be very interesting to investigate the effect of information load and inflectional family on levels of activation using neuroimaging.

2.8 Conclusion

In this chapter I provide further evidence that information theory provides the right tools to investigate lexical access and the mental lexicon in general. I combined Kostiç (1991; 1995; 2003) original measure of information load and Baayen et al's inflectional entropy to provide two new measures for verbal morphology: information load of individual lexemes and inflectional entropy, both combining frequency effects with linguistic factors. Using an auditory lexical decision task on Dutch past tense and infinitive verb forms both factors were found to affect response latencies for a group of young and healthy elderly participants. I suggest that these results demonstrate that the strength of the memory trace for lexical items, and hence their availability for retrieval, depends on the amount of linguistic analyses performed on these items in the course of developing the corresponding memory trace. Our information theoretical measure that takes into account both frequency and linguistic characteristics of an item (number of linguistic functions and meanings) provides a better predictor of the reaction time. Thus, as argued above, it is not merely how often we hear something that determines the accessibility of a lexical item for retrieval but rather how often (on average), the language system performs linguistic analyses on a given lexical item. In comparing young and elderly listeners no group interactions were found, although there were subtle differences in the factors affecting response time for the infinitives for young and elderly participants. These findings suggest that lexical retrieval as measured by information theoretical means does not change with age, although more research possibly using neuro-imaging is required to confirm the reaction time data.

2.9 References

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3 AUDITORY LEXICAL DECISION IN APHASIA

3.1 Introduction

Difficulty with word finding is the most common and, for patients, one of the most frustrating characteristics of aphasia. It is evident in all forms of aphasia, although different forms of aphasia may have specific difficulties with particular classes of words. There is a growing consensus that within the class of content words many patients have particular difficulties with verb production. Regardless of the type or severity of aphasia, retrieval of verbs is problematic for the majority of aphasic patients. Where verbs are produced, they are often uninflected for tense and agreement (Faroqi-Shah & Thompson, 2007; Zuckerman et al., 2001).

Over the last few decades several theories have been suggested to account for verb deficits. Lexical verbs have been the subject of interest in most studies. Lexical verbs, unlike modal, copular and auxiliary verbs, are open-class verbs that have lexical meaning. In addition to providing lexical information, lexical (and other types of) verbs have a grammatical function: their inflected forms express the relationship to the subject of a sentence (agreement) and refer to a time frame (tense). As discussed in chapter two, traditionally inflected verb forms were thought to be formed by deterministic rules. Based on this assumption, theories on why inflected verbs are particularly difficult for many aphasic patients have been suggested. The Tree Pruning Hypothesis (Friedman & Grodzinsky, 1997) for example suggests that tense inflection (unlike agreement inflection) is impaired in non-fluent aphasia due to a syntactic deficit (i.e. the inability to move the verb to the correct node in the syntactic tree).

Contrary to the theories that pose representational deficits as underlying cause for verb difficulties in aphasia, several theories have suggested processing deficits (Avrutin, 2000; Kok et al., 2007) may be the main culprit. These suggest that patients with aphasia are able to compose and produce inflected verb forms, but that a reduced processing capacity makes this tasks particularly challenging.

The current chapter aims to investigate lexical access in aphasia within a reduced processing capacity framework, providing quantitative measures of linguistic material. The data in chapter two showed that processing latencies of verbal material for healthy adults is affected by complexity factors, as calculated within an information theoretic framework. Verbs that have high individual information loads took longer to be identified whilst strong paradigmatic family connections (inflectional entropy) reduced latencies. This chapter sets out to investigate the effect of complexity of verb forms on latencies in an auditory lexical decision experiment performed by aphasic individuals.

3.2 Research Questions Chapter 3

(1) What is the effect of information load of individual lexemes on lexical processing in adults with aphasia?
(2) What is the effect of the inflectional entropy on lexical processing in aphasia?

Based on my findings in chapter 2 my predictions are that (1) people with aphasia have more difficulty with verbs with a higher individual complexity load (information load) and that (2) people with aphasia will have less benefit of the support provided be a strong inflectional family.

Section 3.3.1 discusses literature on lexical access in aphasia and the role of reduced activation and cognitive control. In section 3.3.2 I discuss the literature that shows that processing capacity is reduced in (non-)fluent aphasia. I will then recap the most important notions from information theory and how these can inform research on lexical access in aphasia. Section 3.6 present results of an auditory lexical decision experiment using these measures as predicting factors for reaction time in non-fluent aphasia. I will argue that people with non-fluent aphasia have difficulty selecting a target (an inflected verb form) between competing lexical items (other members in the inflectional paradigm) and that this deficiency becomes particularly apparent for verb forms and families with increased complexity.

3.3 Lexical Access in Aphasia

3.3.1 Lexical Access and the Role of Activation Levels

Lexical access in aphasia has been a much-studied topic. Several explanations have been proposed in the literature for lexical processing impairments. Some involve the notion of activation spreading in the lexicon. In non-fluent aphasia base level activation has been suggested to be reduced for lexical representations (Blumstein & Milberg, 2000; Janse, 2006; Yee et al., 2008) or delayed or slowed, leading to a slower-than-normal time course of lexical activation (Prather et al., 1992; Swinney, Prather & Love, 2000). Others suggest issues with working memory to be responsible for difficulties with lexical access. People with aphasia would have difficulty maintaining the activation of lexical representations in working memory, which leads to a failure in lexical access (Martín, Breedin & Damian, 1999). A third explanation has to do with cognitive control; people with aphasia would have difficulties selecting a target between competing alternatives and therefore be unable to overcome lexical competition (Utman, Blumstein & Sullivan, 2001).

Although these theories have been described as independent, separate accounts of lexical access difficulties in (non-fluent) aphasia, recent research indicates that it is difficult, if not impossible to distinguish between them. Utman, Blumstein & Sullivan (2001) for example set out to investigate reduced activation in non-fluent aphasia using a semantic priming paradigm. They manipulated acoustic features within the prime word to create good and poor exemplars. In healthy adults it has been shown that words containing poorer phonetic exemplars produce less semantic facilitation. This is taken as evidence for a *graded activation framework:* lexical entries may be more or less active, depending on the extent to which the acoustic input constitutes a good match with the stored representation. In addition to the manipulation of acoustic features, the authors distinguished prime stimuli that have a lexical competitor (coat -> goat) or not (cat -> /gaet/). Nine patients with Broca's aphasia were tested. Results showed that similar to healthy adults, semantic priming decreased in words containing poor phonetic exemplars for the aphasic participants. However, in healthy adults this reduction is short-lived and is not influenced by the presence or absence of a lexical competitor. In participants with Broca's aphasia however, semantic priming *was* influenced by competition. For altered prime words with a lexical competitor semantic priming was completely eliminated (*p*ear* with the lexical competitor *bear* fails to prime fruit). The authors argue that this is the result of lowered activation levels overall: poor phonetic exemplars lead to low activation levels in both the target and competitors (due to spreading of activation in the network). As activation is very low to begin with, the system fails to distinguish the target from its competitors. Although the authors set out to investigate activation levels in aphasia, they acknowledge that these results could also be explained by an impairment in selection of a target amongst competitors. This account is further supported by the fact that most of their participating aphasic patients had damage to the left inferior frontal gyrus, an area recently implicated in conflict resolution in the presence of competing representations (cf. Novick et al., 2005). Of course it is plausible that a combination of reduced activation and an impairment in selecting an item from competing entries leads to difficulties with lexical access and retrieval. Alternatively, it can be that reduced activation in the lexical network *causes* conflict resolution difficulties.

Further evidence that lexical access difficulties may be due to a combination of reduced activation and selection comes from eye tracking studies. Yee, Blumstein & Sedivy (2008) use a visual world paradigm (VWP) to investigate lexical activation in Broca's and Wernicke's aphasia. In VWP studies on word recognition participants are typically presented with 4 pictures: a target, an unrelated foil and at least one distractor that is a (phonological) competitor of the target word (e.g. window-windmill, or window–door for a semantic trial). Upon hearing the target word, participants typically fixate longer on the (phonological) distractor than on unrelated foils. This is true for both onset (cohort) and rhyme competitors (beaker-speaker) and semantic foils. Yee et al. showed that patients with Broca's aphasia fail to fixate longer on a phonological distractor with the same onset as the target (logs-lock) and on items that are semantically related to the phonological foil (key via lock). If difficulty with lexical access were only due to difficulties selecting the target amonst distractors, *increased* fixations on distractors would be expected. Instead, it seems that due to decreased activation the distractors fail to become (significantly) active.

In a follow-up study Mirman et al. (2011) performed an eye tracking study on 6 participants with Broca's aphasia and 4 with Wernicke's aphasia investigating rhyme competition effects (carrot-parrot) and combining the findings on this experiment with the cohort competition effect data from Yee et al. (2008). In addition to the VWP experiment, they used computational modelling to predict patterns of outcome in both groups of aphasic participants. They used the TRACE model (a connectionist model of word recognition) to investigate whether reduced activation, delayed activation, early perceptual impairments or a disruption in response selectivity (selection of target amongst distractors) would best match the eye tracking data. The behavioural results revealed greater rhyme competition in Broca's aphasia in comparison to healthy controls and participants with Wernicke's aphasia and greater cohort effects for people with Wernicke's aphasia. Using various manipulations on the TRACE model the authors found that only one account was compatible with the behavioural results of both groups of participants: changes in *response selectivity* led to opposite effects on cohort and rhyme competition. This account can explain the findings for both groups of aphasic patients; in Broca's aphasia response selectivity is reduced, giving rise to large rhyme competition effects, whilst in patients with Wernicke's aphasia the selectivity is increased, leading to large cohort competition effects.

Most of the research on reduced lexical activation in aphasia has focussed on nouns. However, research on frequency effects in aphasia show that disturbances in activation levels could also play an important role in the retrieval of verbs. Frequency effects have been taken to be indicative of ease of retrieval of items from the mental lexicon. All other things being equal, frequent words are more readily perceived than rarer forms (Howes & Solomon, 1951; Baayen et al., 2006). It is argued that high frequency words have a higher rest activation, and need less extra activation to exceed the threshold value for recognition than low frequency words (Dell, 1990). Stemberger (1984, 1985) suggested that difficulties retrieving verbs and particularly verb inflection errors might be determined by frequency. Research by Faroqi-Shah & Thompson (2004) is consistent with this prediction, word form (lexeme) frequency emerged as a significant predictor of both accuracy and substitution errors in their study in which non-fluent aphasic participants were asked to produce inflected verb forms in a picture naming paradigm. In a constrained subject-verb agreement task, Janssen & Penke (2000) failed to find frequency effects on inflection production performance by non-fluent aphasic speakers. Crucially, performance was very high on this task (only 7% errors) so it may well be that frequency effects were not found due to a ceiling effect. Frequency was found to play a role in spontaneous speech by Centeno et al. (1996) who showed that present and past tenses, the most frequently used tense forms in Spanish, to be better preserved in Spanish agrammatic aphasic participants.

Combining the results of the eyetracking studies and frequency effects it seems that people with non-fluent forms of aphasia have reduced levels of activation in the lexicon, which leads to (or is combined with) a reduced ability to select a target among competing (lexical) entries. In the present study I will further investigate this difficulty from a new point of view, using a mathematical model, but first I will discuss literature that shows lexical access becomes particularly difficult when cognitive load is increased.

3.3.2 Verbal Inflections and the Role of Computational Load

For people with (non-fluent) aphasia retrieval of (inflected) verbs is notoriously difficult. Difficulties with inflected verbs have mainly been investigated in relation to sentence production. Specific difficulties with inflections have been looked at in the context of generative grammar by comparing tense and agreement inflection. The two most influential studies suggest that in a syntactic tree the node related to tense is located high and therefore unavailable in Broca's aphasia (Friedmann & Grodzinsky, 1997), or that tense is underspecified in aphasia (Wenzlaff & Clahsen, 2004). As discussed by Kok et al. (2007) these representational accounts have difficulties explaining variation between and within patients. If problems are caused by a loss of linguistic knowledge one would expect performance to either be at chance or below at any moment and task at hand. Complexity of the task or lexical items used in the task should not influence performance. Recent research however shows that task and lexical complexity do influence performance.

Evaluating tense inflection in aphasia Avrutin (2000) suggests that tense difficulties are not due to syntactic problems, but that tense production is computationally complex as it involves integration of syntactic and discourse information. In tense production both discourse information and grammatical information have to be integrated to come up with the right verb form (this in contrast to aspect production in which only grammatical information is needed). It is the integration of information that leads to an overload of the computational capacity of the aphasic individuals, not a disruption in representational knowledge of one or both of the individual components. Further evidence for a reduced processing capacity in aphasia comes from Hartsuiker, Kolk & Huinck (1999). In their study Dutch people with Broca's aphasia and age-matched peers were presented with preambles such as (1) and (2) in a sentence completion task.

(1) The baby on the blankets

(2) The label on the bottles

Although both preambles require a verb with singular inflection, there is a difference in the interpretation of the preambles: in (1) there is only 1 baby on multiple blankets, whereas in (2) there is one label for each bottle (and thus as many labels as bottles). Hartsuiker et al. found that healthy adults are more likely to make inflectional errors in type (2) sentences. They are sensitive to both grammatical and conceptual information within the sentence. Aphasic participants on the other hand, did *not* differ in performance between sentence type (1) and (2), although they performed significantly worse than the control participants overall. The authors argue that this is because the participants with aphasia were unable to take both grammatical *and* conceptual information into account. In order to keep processing to a minimum and avoid computational overload, these individuals use only essential grammatical information.

Further evidence that problems with producing inflected verbs are not due to representational deficits, but rather occur when there is a computational overload in aphasia comes from work by Bastiaanse et al. (2001; 2011). Bastiaanse and colleagues looked at the trade off between verb inflection and verb diversity. In several papers they showed that patients with Broca's aphasia *can* produce inflected verbs, but that this has an effect on the number of different verbs they produce in a given conversation. When the proportion of finite verbs produced is normal, verb diversity is lower than in healthy speech, and when verb diversity is within normal range, verbs are often uninflected. The authors suggest that it is not so much the syntactic representation or verb retrieval that is impaired in these participants, but rather the interaction between the two. Finite verbs can be produced, but at the cost of verb diversity.

Processing limitations in aphasia were further investigated by Kok, van Doorn & Kolk (2007). They used a classic design from psychological research, the dual task design, to investigate inflectional errors in aphasia. Dual task designs require a participant to perform 2 tasks (most often in different modalities) simultaneously. Performance on the dual task is then compared to a base condition in which only 1 task was performed. If performance on the dual task is significantly worse than during the base condition, it is argued that there is a difficulty with the processing load. Kok et al. designed two tasks: in the first task participants had to produce verb inflections while the word order of the sentence constituents was given. In the second task both word order and inflection needed to be produced. Performance on production of inflection was then compared for both tasks. The results showed a significant drop in performance on inflection production for the dual task, indicating that task complexity influenced performance for the aphasic participants. This was true for both regular and irregular verbs. The authors argue that these results point towards a processing account for inflectional difficulties in aphasia.

Summarising the discussed literature so far it is evident that processing load plays an important yet still somewhat undetermined role in verbal inflection in aphasia. An increase in cognitive load, be it by presenting participants with a more complex task, or unconsciously favouring verb diversity at the cost of verb inflection, leads to profound problems with the production of inflected verbs. Literature on lexical access and retrieval shows that there may be reduced activation in the lexicon in people with aphasia which, combined with difficulties selecting a target, leads to problems activating lexical items in conversation. The current study sets out to combine these two lines of research and to investigate lexical access of verbal forms in aphasia. The hypothesis is that the verb retrieval difficulties people with aphasia experience are due to a combination of the complex nature of inflected verb form and a reduced processing capacity in aphasic individuals. Chapter two presented a tool to measure complexity of individual verb forms and in this chapter I investigate how complexity of individual verb forms affects latencies for lexical access in people with aphasia. It is crucial to emphasis that (as discussed in chapter two), I assume all inflected forms are stored in long-term memory. I hypothesise that it is the process of activating and selecting the correct verb form within its paradigmatic family that is difficult for individuals with aphasia due to reduced processing, not the process of adding an inflection to a stem of a verb form retrieved from long-term memory. A recap of the most important notions from information theory will be discussed in the next section.

3.4 Information Theory Application to Processing in Aphasia

As discussed in previous chapters information theory is a branch of mathematics and engineering that is involved with uncertainty and the quantification of information. Within psychology and psycholinguistics it has often been used to investigate processing cost and specifically the balance between maximisation of information transfer and the cost of communication imposed by limitations of the human brain. In psycholinguistics it has been applied amongst other things to measuring the cognitive cost of semantic processing of lexical items (McDonald & Shillcock, 2001); the structure of the whole lexicon (Ferrer i Cancho, 2006); article production (de Lange, 2008) and inflectional paradigms (Moscoso del Prado Martín, Kostiç & Baayen, 2004).

Morphological processing of nouns and verbs by healthy adults has been extensively researched by Kostiç and colleagues (Moscoso del Prado Martín, Kostiç & Baayen, 2004; Baayen, Feldman & Schreuder, 2006; Milin Filipovic Durdevic, & Moscoso del Prado Martín, 2009). They described several measures for the informational complexity of a word both in terms of the amount of information contained by the target word itself (information load) and the amount of information carried by its morphological paradigms (derivational and inflectional entropy). They show that these measures explain variation in reaction times in lexical decision tasks for healthy adults. The findings of the auditory lexical decision task on healthy adults in chapter two were in line with this work. Verbs that have high individual information loads took longer to be identified whilst strong paradigmatic family connections (inflectional entropy) reduced latencies.

In healthy adults these findings are subtle and only show up in experimental settings. In spontaneous speech it does not take longer to produce or comprehend "*speelde*" with an information load of 4.10 in comparison to "*liep*" with an information load of 1.5 (cf. chapter 2:p.18). Findings in the aphasia literature discussed above suggest that people with aphasia may have reduced lexical activation and specific difficulties selecting targets amongst competitors. Furthermore, verb retrieval has been shown to be particularly difficult for these people and susceptible to increased processing duration. The current chapter therefore set out to investigate the effect of complexity of verb forms, as measured by the information theoretic measure of information load and inflectional entropy. It provides us with the possibility to make quantitative predictions about the performance in aphasia and relate the findings to the literature discussed. This chapter reports on an auditory lexical decision experiment that was introduced in chapter two, performed by a group of aphasic participants. My predictions are that (1) people with aphasia will have longer latencies for verbs with a higher individual complexity load as measured by the information load (I) and that (2) latencies of people with aphasia will be show less benefit of the support provided be a strong inflectional family (H).

3.5 Materials and Method

3.5.1 Participants

Two groups of adults participated in this experiment. Twenty aphasic participants were recruited via local rehabilitation– and aphasia centres. All participants were monolingual native Dutch 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 most suffered a unilateral lesion resulting from a cerebrovascular accident. One patient had suffered multiple infarcts and one patient had suffered from meningitis. Their performance did not differ from the other participants in the group and as this study did not set out to find neural correlates for behavioural data it was decided to include these participants. Onset of aphasia was at least 6 months prior to testing for all participants. All participants had normal or corrected to normal vision and no known oculomotor deficits. One participant was excluded from the analysis as she had pre-morbid (developmental) dyslexia. Two participants were excluded because they were unable to perform the auditory lexical decision task. Furthermore, fluency was used as an additional inclusion criterion in this study. Only patients described as non-fluent by their speech therapist were included. The remaining 17 participants were able to understand the experimental task and performed well above change on the six practice trials. The token test (part of the Dutch AAT (Graetz et al., 1992) was administered to confirm the presence of aphasia. As suggested by Heesbeen (2001) a cut-off score of 7 errors was used for the diagnosis of aphasia. Fewer than 7 errors indicate no or rest aphasia. Diagnosis of aphasia was based on the local speech therapist's assessment as well as an analysis of spontaneous speech samples by the author and an independent speech and language therapist. The Ruff Figural Fluency task (Ruff, Light & Evans, 1987) was administered to control for non-verbal initiation, planning, and divergent reasoning. All participants performed within normal limits on this task. Further information about these participants can be found in table 1.

	Gender	Age	Onset	Aetiology	Profession/level of education	Ruff FF (perc)	TT (50-0)
AD	Female	61	1998	iCVA-left	Secretary	54%	28
BL	Male	64	2009	iCVA-left	Representative	22%	13
HA	Male	33	2008	Meningitis	Civil engineer	50%	37
TV	Male	77	1996	iCVA-left	Technical director	24%	33
JJ	Female	63	2004	iCVA-left	Taxi driver	84%	24
JH	Female	36	2003	Multi-infarct	Social worker	5%	9
JL	Male	60	1999	iCVA-left	HBS	40%	29
LV	Female	58	2006	iCVA-left	Administration	30%	7
LiV	Female	55	2008	iCVA-left	Salesperson	46%	17
MN	Male	48	2009	iCVA-left	Accountant	35%	48
SB	Male	61	1995/2004	hCVA left	Minister	24%	33
SS	Male	57	2002	iCVA-left	Skipper	58%	10
SK	Female	65	2005	Aneurism left	Translator	34%	8
SV	Male	42	2005	iCVA-left	Civil engineer	38%	8
DO	Male	64	2006	iCVA-left	Administration	46%	41
MK	Female	42	2009	iCVA-left	BA	61%	36
PG	Female	46	2008	iCVA-left	Unknown	54%	27

Table 1. Aphasic participant information.

The healthy elderly participants described in chapter two were matched to the aphasic participants on age and years of education. Mean age for the elderly control groups was 62yrs (SD 9.1yrs), mean age for the group of aphasic participants 58yrs (SD 10.7yrs). Independent t-tests revealed no significant difference for the two groups.

3.5.2 Stimulus materials

Stimulus materials used in this experiment were identical to those used in chapter 2. 286 simplex verbs were used; 143 regular and 143 irregular verbs.

Lemma frequencies were matched for regular and irregular verbs. The list consisted of past tense forms only. 286 phonotactically legal pseudoverbs were pair wise matched to the real verbs. I chose to use only one list for the aphasic participants, as the experiment would become too long if they were presented with all lists and groups would become too small if I divided the lists between participants. Past tense is known to be particularly difficult for people with aphasia and the previous chapter showed clear results on this list for the healthy elderly participants.

3.5.3 Procedure

The procedure was identical to the procedure described in chapter 2. Reaction times were measured from target offset until the button press. The experiment was split up into two sessions, each lasted about 20 minutes. Participants were given a short break halfway through in both sessions. There was not more than 1 week in between session 1 and session 2. If participants preferred to participate in both sessions on the same day, they were given at least an hours' break in between sessions.

3.5.4 Calculation of statistical measures

As described in the introduction, two measures from information theory were used, namely information load and inflectional entropy. In addition several other factors were taken into consideration in the analyses as described in chapter 2. I will provide a quick recap: Frequency counts were entered into the analyses (both lemma and form frequency) and to investigate possible effects of semantic neighbourhood I used number of synsets (Tabak 2010).

Information load

Information load was calculated as described in chapter 2

[1] $$I_e = -\log_2\left(\frac{F_e/R_e}{\sum_e F_e/R_e}\right)$$

in which I equals information load of verb form (e), F the frequency of the verb form and R the number of grammatical functions the verb form can fulfil. Unlike in previous work, information load was not averaged for a given exponent, but rather information load of individual verb forms were calculated.

Inflectional family size: entropy (H)

Inflectional entropy was calculated as described in chapter 2: frequency for each verb form in a paradigm was extracted from CELEX. For each verb form the number of grammatical functions that specific form can fulfil in Dutch was calculated. F/R was then calculated for each inflected form of a given verb. This value (rather than probability of occurrence only) was used to calculate the inflectional entropy for each verb.

[2] $$H = -\sum p \log p$$

in which p equals (4)

[3] $$p = \frac{F_e/R_e}{\sum F_e/R_e}$$

in which F_e represents the probability of a verb form within its inflectional paradigm and R the number of grammatical functions that verb form can fulfil.

3.6 Results

Reaction times and error rates were measured for all participants. For both groups 1.5% of data were missing. In these cases no button was pressed within the allotted time. Reaction times and error rates for both groups are reported in table 2.

	Mean RT (SD)	**Correct % (SD)**
Aphasia	1146 (520)	84% (7.8%)
Control	798 (400)	94.1% (2.3%)

Table 2. Mean reaction time and percentage correct on the auditory lexical decision task for aphasic and control participants.

Mann-Whitney tests revealed significant differences between the groups in reaction time ($p<0.01$) and number of errors ($p<0.01$).

The distribution of the latencies was highly skewed. For further analyses I reduced this skewness by means of a logarithmic transformation. Distributions were checked for normality. Only correct answers were used for further analyses. Each list and group was analysed individually to investigate the effect of our information theoretic measures in reaction times. First, correlations between reaction time and individual factors were investigated. Next a linear mixed model analysis was performed to the data for each group with participant and verb as crossed random effects. Then both groups were entered in a large linear mixed model to investigate possible group differences. All main effects and interactions were investigated. For reasons of space the tables and figures below only report those predictors and interactions that reached significance.

Results for the control group were reported in chapter 2, but will be repeated here for ease of comparison to the aphasic group. Significant correlations to response latencies were found for: inflectional entropy ($F(1,2635)=14.921$, $p<0.001$); information load ($F(1,2617)= 4.963$ $p< 0.05$) and number of synsets ($F(1, 2644)=17.166$, $p<0.001$).

For the aphasic participants significant correlations were found for: inflectional entropy ($F(1,5046)=9.392$, $p<0.01$), lemma frequency ($F(1,5064)=4.177$, $p<0.05$) and number of synsets ($F(1,5064)=19.412$, $p<0.001$).

Regression graphs are presented below for each significant correlation.

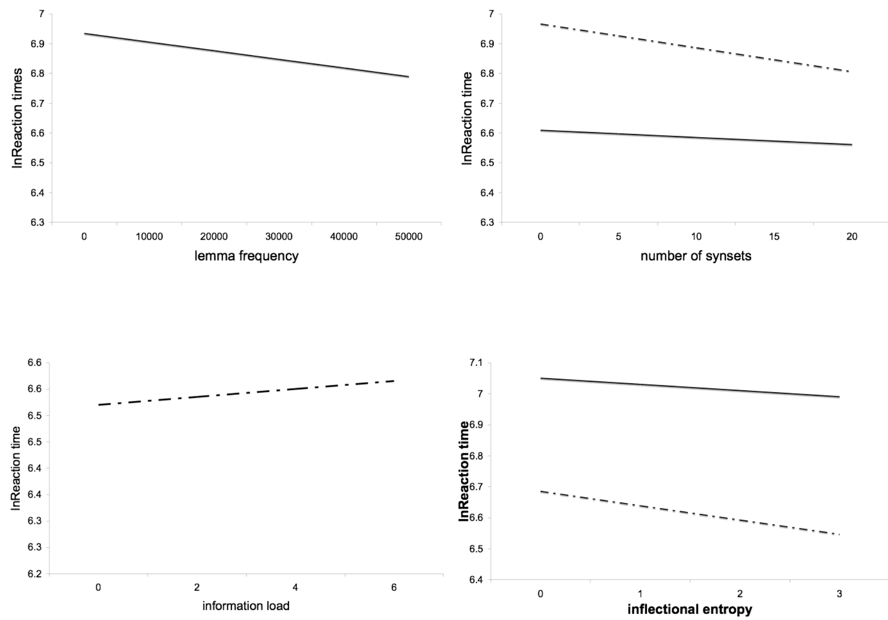

Figure 1: Regression lines for significant correlations between lnReaction times and independent factors lemma frequency, number of synsets, information load and inflectional entropy. Dotted lines represent control participants, solid lines the aphasic group. For lemma frequency there was no correlation with lnRT for the control group, for information load there was no correlation with lnRT for the aphasic participants.

A linear mixed model analysis was then performed for each group with participant and verb as crossed random effects. All main effects and interactions were investigated. The tables below display the estimated coefficients of the predictors in the multilevel model fit to response latencies of the lexical decision experiment.

For the aphasic participants:

	Estimate	**Std error**	***Df***	***t***	**Sig.**
Intercept	7.1358	0.079	49.672	90.061	.000
Regularity	-.1156	.0190	280.445	-6.083	.000
nSynsets	-.0118	.0033	282.164	-3.501	.001
Infl entropy	-0.050	.0248	280.758	-2.033	.043

Table 3. Multilevel analyses on the reaction times for the aphasic participants

For the control participants:

	Estimate	**Std error**	***Df***	***t***	**Sig.**
Intercept	6.8607	.0983	28.167	69.726	.000
Regularity	-.1384	.0240	278.846	-5.748	.000
Infl entropy	-.0869	.0042	275.484	-3.443	.001
nSynsets	-.0146	.0312	276.093	-2.784	.006

Table 4. Multilevel analyses on the reaction for the control participants

Finally the results of the aphasic and control group were combined and a linear mixed model analysis with group as a main factor was performed to investigate possible interactions between the group and other factors. A significant interaction was found for group x inflectional entropy ($F(1,7545)=3.648$, $p<0.05$). The effect of inflectional entropy was stronger for the control group than the group of aphasic participants.

3.7 Discussion

The current chapter investigated word recognition of verbs in aphasia using an auditory lexical decision task. The effect of several independent factors on latencies of a group of aphasic speakers and healthy controls were investigated.

Measures from information theory were used to calculate the complexity of individual verbs forms as well as the complexity of the inflectional family of each verb. As discussed in the introduction, lexical access in aphasia may be affected by reduced levels of activation in the lexicon (Yee, Blumstein & Sedivy, 2008). Furthermore, the ability to select targets between (lexical) competitors has been suggested to be impaired (Mirman et al., 2011). From research on the production of inflectional morphology we know that increasing processing load (e.g. through means of a dual task) decreases performance, indicating that processing capacity is reduced in aphasia. Combining these lines of work the research questions for this chapter were therefore:

(1) What is the effect of information load of individual lexemes on lexical processing in adults with aphasia?
(2) What is the effect of the inflectional entropy on lexical processing in aphasia?

The predictions were that people with aphasia have more difficulty with verbs with a higher individual complexity load and have less benefit of the support provided by a strong inflectional family. I will now first discuss the results of the auditory lexical decision experiment after which I will turn to the implications for theories of lexical retrieval difficulties in aphasia.

Seventeen patients with non-fluent aphasia and ten age and education-matched peers participated in the lexical decision experiment. Half of the presented past tense verbs were regular, half irregular. For all past tense verb forms information load and inflectional entropy was calculated. Inflectional entropy is a measure that reflects probability distributions within an inflectional paradigm. As discussed in the introduction, when members within an inflectional paradigm are very similar in terms of their probability distribution (based on frequency and the number of functions each inflected form can fulfill), entropy is high. In production tasks inflectional entropy has been shown to have an inhibitory effect on latencies (Tabak, 2010). It is thought that this reflects the process of lexical competition. In recognition inflectional entropy has a facilitatory effect; inflected verb forms from families with high entropy are processed faster than words those from low entropy families. In chapter two I suggested that this effect reflects properties of spreading activation. Upon hearing a target word, the correct word form is activated and activation spreads to members of its (inflectional) paradigms. In terms of neural network modelling, words in high entropy inflectional paradigms have short and strong connections. In psychological terms closeness in probability distribution means more equality among base levels of activation. In high entropy families activation of the family members boosts the activation level of the target, which results in shorter latencies for the target (it is faster in reaching the threshold). Our findings are in line with this: both groups show a facilitatory effect of inflectional entropy in the auditory lexical decision experiment. The assumption is that memory traces are present for all inflected verb forms and that there are tight connections between members of inflectional paradigms. In aphasia these connections are still present, but processing of information (expressed in bits) is less efficient, as indicated by the interaction between group and inflectional entropy present in the multilevel analyses. Inflectional entropy does have a facilitatory effect for aphasic individuals but to a lesser degree than for healthy controls. I propose that reduced base level of activation in the lexical network of people with aphasia results in a less pronounced effect of changes in the inflectional entropy. Informally, making an already difficult task somewhat more difficult (e.g. decreasing H for people with aphasia), has less effect than making a relatively easy task more difficult (e.g. decreasing H for healthy adults). Strong (facilitatory) effects in healthy processing therefore flatten in processing in aphasia.

Information load is a measure of individual complexity. It is based on frequency of the verb form and the number of grammatical functions that form can fulfill and can be viewed as an index of the strength of the memory trace. Research in healthy young and elderly participants has shown that information load is an important predictor of reaction time. Words with high information loads are processed slower than those with low information load (Kostiç, 2003). The results for the healthy controls, as also shown chapter 2 support this: verb forms with high information load have longer RTs. Complexity as measured by our information load measure reflects the process of selecting a target between lexical competitors in the mental lexicon and bringing the target to the threshold of activation. I therefore predicted that due to reduced processing capabilities and difficulties in selectivity in aphasia, our aphasic participants would show a strong effect of information load. However, the results show that information load is not a predicting factor in the reaction time data of our aphasic participants. Although the hypothesis can therefore not be confirmed or rejected, the finding that there is no correlation in reaction time and information load for our patients is interesting as this correlation *was* found for the healthy controls. Combined with the finding that inflectional entropy did affect reaction times, but to a lesser degree than in the healthy participants, I suspect that the lack of an effect of information load is due to a floor effect.

This can be explained by looking at the possible shape of the curve of the effect of information load on reaction time. Information load is unlikely to have a completely linear effect on reaction time. Instead, I suggest the curve is logistic (see figure 3). For the healthy individuals this experiment captures performance at the seemingly linear part of the curve. If we were to compare performance on very low, or high information load items only we would probably not find any effect as the slope of the curve is near to zero at those points. I propose that, due to reduced lexical activation, processing of information in bits in aphasia is reduced and that performance of the aphasic patients on this experiment is captured by the last part of a logistic curve (a flat line as shown in figure 4). Processing even the items with relatively low information load is already difficult for people with aphasia.

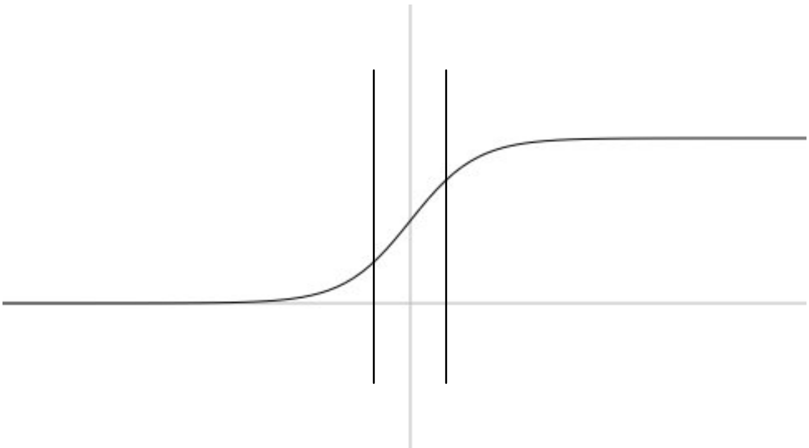

Figure 3. Proposed shape of curve of effect of information load on reaction time in healthy adults, with RTs in the lexical decision experiment captured between the two vertical lines.

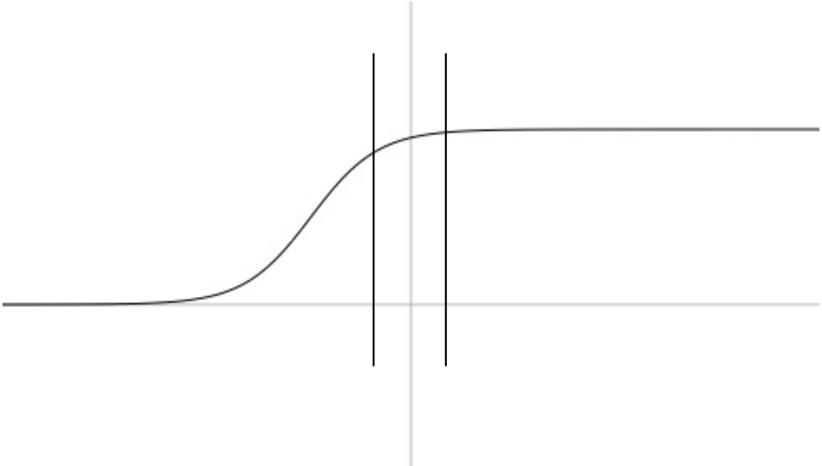

Figure 4. Proposed shape of curve of effect of information load on reaction time in aphasic adults, with RTs in the lexical decision experiment captured between the two vertical lines.

In line with previous research (Faroqi-Shah & Thompson, 2004) lemma frequency showed a correlation with reaction time for the aphasic participants. The effect however was outperformed by the information theoretic measure of inflectional entropy in the multilevel analyses, indicating that the information theoretic measure is a stronger predictor of processing time.

An important facilitatory factor in lexical access for both groups was number of synsets. This measure is semantic in nature and as described by Tabak (2010) estimates how many distinct meanings one verb has. One synset in WordNet represents one underlying lexical concepts and can usually be expressed by multiple verbs. Moreover, one verb may occur in multiple synsets, indicating it has several distinct meanings. Semantic associations have been found to be a predictor in processing for both healthy and aphasic individuals before (cf. Buchanan et al., 2001; Mirman & Magnuson, 2008; 2011). In line with this research I found that a higher number of synsets has a facilitatory effect on processing; reaction times decrease for verbs with high synset scores. This effect is independent of frequency, even though it is the case that verbs with more synsets are often also more frequent. Performance was very similar in aphasia and healthy controls. I suggest that this indicates that the (semantic) structure of the lexicon does not differ for people with aphasia and healthy controls. This finding is in line with van Egmond, van Ewijk & Avrutin (cf. chapter 5) who investigated the organisation of the lexicon in aphasic and healthy adults using Zipf's law (a power law used to describe frequency distributions) and found that aphasic speech conforms to Zipf's law suggesting that the basic organisation of the lexicon is the same for both groups.

3.8 Conclusion

This chapter set out to investigate processing difficulties in people with aphasia using quantitative measures from information theory. Information theory provides tools to quantify distinguishability between distractors and targets in (verbal) paradigms. This has been related to processing cost in healthy adults. Reduced processing ability in aphasia has been suggested as a possible factor in difficulties with lexical retrieval. The results reported in this chapter support the view that processing is reduced in aphasia but I take this proposal further: this work demonstrates that it is the capacity to process (lexical) information (as measured by information-theoretical means) that suffers in aphasia. For the aphasic participants facilitatory effects of inflectional entropy were reduced and information load did not predict reaction times. I therefore propose that the qualitative nature of the underlying lexical network in aphasia remains intact, but the capacity to activate units of this network is decreased, in a quantitative way measurable by information theoretical tools.

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4 VISUAL SEARCH IN APHASIA

4.1 Introduction

In the previous chapter it became clear that people with aphasia have linguistic processing difficulties, which can be captured using two measures from information theory. The overall organisation of the lexicon seems unchanged (as will also discussed in chapter 5) as the same measures affect reaction times in the same way for both aphasic and control groups. However, when complexity of verbal items is manipulated systematically quantitative differences occur. When manipulating the complexity of a verbal paradigm (inflectional entropy) the facilitatory effect on reaction time seen for healthy adults is less pronounced for people with aphasia. It seems that dealing with uncertainty and selecting a target from a family of distractors is difficult for people with aphasia and they are less able to benefit from increased entropy in a verbal paradigm than control adults and have more difficulties processing complexity of individual forms, expressed in bits. The obvious and interesting question arises whether this processing difficulty is limited to verbal material, or whether similar difficulties processing complex information can be seen in other cognitive domains for people with aphasia. The current chapter will address exactly that question, using a visual search paradigm.

The chapter will start with an overview on research investigating non-verbal skills in people with aphasia, followed by a short overview on visual search. I then discuss the results of a visual search experiment on ten healthy and aphasic participants.

4.1.1 Non-verbal Cognitive Skills in Aphasia

The relation between language and other aspects of cognition of individuals with aphasia has received increasing attention over the last 2 decades. Where aphasia was traditionally viewed as a language-specific impairment (Benson, 1994; Grodzinsky, 1990), more and more research suggests that problems in other cognitive skills may aggravate on (Murray, 1999) or even underlie aphasic behaviour (McNeil et al., 1991). This has also become apparent in recent papers on aphasia treatment; non-verbal cognitive measures have been found to correlate (Seniów et al., 2009b) and even predict (Hinckley et al., 2001) success of linguistic goals in treatment.

As discussed by Helm-Estabrooks (2002) cognitive skills can be divided into five primary domains: attention, memory, executive functioning, language and visuospatial skills. Most work on aphasia has looked into the role of attention and (working) memory in correlation to language deficits. Working memory refers to the ability to simultaneously (temporarily) store verbal and non-verbal information and to make them available for further processing. The most influential model in the working memory literature is that of Baddeley and Hitch. They propose a multicomponent model in which a 'central executive' is responsible for integration and coordination of three 'slave systems': the phonological loop, the episodic buffer and the visuo-spatial scratchpad (Baddeley, 2000). Although this is still the most-used model in the literature, it has received much criticism (cf. Postle, 2006). The debate on how working memory works and which model captures this cognitive skill best is still ongoing. As a result, the literature reporting on experimental ways to capture this skill is fractionated, even in the literature on healthy people. Regardless of the lens through which WM is viewed, numerous studies have made clear the centrality of WM to both higher-level cognitive processing as well as to language processing. Numerous studies demonstrate WM limitations affect many aspects of linguistic and non-linguistic processing (e.g., Caplan & Waters, 1999; Christensen & Wright, 2010; Friedmann & Gvion, 2003; Sung et al., 2009) in adults with aphasia. Mayer & Murray (2012) for example used an n-back task using both linguistic and non-linguistic information to investigate working memory. The n-back task involves judging whether a current stimulus matches one that occurred n places back in a sequence. They used: three levels of WM load (0, 1, and 2). For the non-linguistic task pictures of faces were used. Aphasic participants' performance was significantly poorer than that of healthy adults as n-levels increased. As our experiments do not rely on working memory I will not present a complete overview on WM in aphasia. It suffices to say that the literature on working memory in aphasia supports the concept that PWA have non-linguistic difficulties in addition to their language disorder.

4.1.2 Attention in Aphasia

A large bulk of research on cognitive skills in aphasia has focussed on attention. Like many cognitive constructs, such as working memory, many definitions and architectures of attention have been proposed. This makes comparison of studies on attention in healthy and language-disordered individuals challenging to say the least. Although varying in terminology, many of these models depict attention as a capacity-limited system (Kahneman 1973, Kinsbourne & Hicks, 1978; Navon & Gopher, 1979; Norman & Bobrow, 1975; Wickens 1980). Two basic assumptions are shared by these capacity models of attention: (a) we have one or more pools of attentional resources that are quantitatively limited; and (b) we can simultaneously deploy and allocate available attentional resources to one or more activities. Several different types of attention are described in the literature: sustained (i.e., maintaining one's ability to respond consistently over time) attention; selective attention (i.e., selecting relevant stimuli or disregarding irrelevant stimuli), attention switching (i.e., shifting focus between tasks or between stimuli with a task) and divided attention (i.e., simultaneously responding to two or more relevant stimuli, tasks, or task demands). A number of investigators propose that the general limit on human attentional resources may be useful for helping to explain some or all of the language problems in aphasia (e.g., Caplan & Waters, 1999; LaPointe & Erickson, 1991; McNeil & Kimelman, 1986; McNeil, Odell, & Tseng, 1991; Murray, 1999; Murray, Holland & Beeson, 1997a, 1997b; Slansky & McNeil, 1997; Tseng, McNeil, & Milenkovic, 1993). The main tenet of this theory is that people with aphasia may have even more limited resources than healthy speakers and/or that they have difficulty in efficiently allocating their attentional resources during (language) tasks.

Research on (divided) attention often uses a dual-task design to test the capacity and efficiency of our attentional system. Most research has been carried out by McNeil & Murray and colleagues (Arvedson & McNeil 1986, Campbell & McNeil 1985, McNeil, 1981, 1982, 1983, 1997, McNeil & Kimelman 1986, McNeil et al., 1991, Tseng et al., 1993; Murray, Holland & Beeson, 1995; 1997; 1998, cf. a review Murray, 1999). In a dual task design a participant is asked to perform a (linguistic) task alone and the same task again simultaneously with another (non-linguistic) task. If both tasks tap into the same attentional resources, one expects performance of the primary task to decrease upon presentation of the second task. Therefore, if aphasic performance is associated with attentional impairments as opposed to purely linguistic impairments, aphasic speakers' performance of the primary, linguistic task should be much better during the least demanding, single-task condition. In contrast, during the more demanding, dual- task condition, performance for that same task should deteriorate significantly. Murray (1999) presents an overview of the studies that used this design to investigate divided attention in aphasia. This is exactly what these studies find: the deterioration of performance on the primary tasks is significantly greater for aphasic speakers than for healthy control adults (cf. Murray et al., 1997a;1997b). In a detailed study investigating all subtypes of attention (i.e., visual and auditory sustained and selective attention, visual and auditory attention switching, divided attention, visual neglect, presence and frequency of daily behaviors indicative of attention problems) Murray (2012) found that her group of aphasic participants performed significantly worse than the control group on all attention measures. Furthermore, she found that the aphasic group also performed more poorly than the control group on the other cognitive tests, assessing aspects of memory and executive functioning which may (in part) depend on attentional capacity.

4.1.3 Visual Search

The studies on working memory and attention show that unlike previously thought, aphasic speakers have difficulties in other cognitive domains than just language. In this chapter I want to further investigate these difficulties using a simple visual search task. Unlike previous research I am not so much interested in whether the aphasic participants perform worse overall, but whether there is a greater deterioration of performance of the aphasic participants as task complexity is manipulated. Unlike the studies on attention, complexity is not manipulated by introducing a second task, or by requiring participants to sustain attention over prolonged periods of time. Instead, a visual search task is proposed in which complexity is modified by altering individual search displays.

Visual search tasks typically involve searching for a target item when it is presented among several distractor items. Findlay & Gilchrist (2003) suggest that two factors affect the way the eye movements are guided in visual search in search for the target. The first is a similarity effect; this effect leads saccades (eye movements) towards items that are similar to the target. The second is a proximity effect; this effect leads saccades being directed to items close to the visual axis. The strength of this effect depends on the display, in terms of both item density and item salience. The effect can almost completely be overridden by the similarity effect when the target item is salient, as in 'pop-out'. Findlay and Gilchrist propose that the display is monitored in parallel, but with increasing weighting for proximity to the projection of the fovea in visual space. This leads to the concept of a salience map, a representation formed from the retinal information. The realisation of the map may be envisaged as through the pattern of neural activity in the neural network. The level of neural activity at each point encodes the salience. Items sharing a feature with the target item will have higher neural activity than other distractor items. The saccade is made to the item with the highest neural activity on the salience map. In simple search tasks item salience is very high, the first saccade is directly made towards the target. In difficult search tasks the target does not pop out, the first saccade is made towards an item with high neural activity. If this item is not the target, the display is monitored again and the next saccade is made towards another item with high neural activity.

Bruce & Tsosos (2009) have used an information theoretic approach to explain saliency in visual displays. They provide a computational framework for visual saliency: Attention based on Information Maximization (AIM). Similar to the work on linguistic material, Bruce & Tsosos (in line with Attneave, 1954) suggest that visual processing is concerned with expectancies and surprise. They provide the following example (see figure 1): if someone were presented with the display on the left, they would have certain intuitions about the scene under the blacked-out circles. For A and B these intuitions largely match the reality as shown in the display on the right. The surprise for area C however, is much greater. If one were to guess what was present under the blacked-out circles, C would by far take the largest number of guesses. This region is therefore the most informative in Shannon's sense.

Figure 1. An example taken from Bruce & Tsosos (2009:3) of how context shapes our expectation of scene content. The content hidden behind regions labeled A and B come close to one's expectation while that hidden by C is arguably quite different from what one would guess. C carries the most surprisal or carries the greatest self-information in a Shannon sense.

Bruce & Tsosos main premise is:

"that the saliency of visual content may be equated to a measure of the information present locally within a scene as defined by its surround, or more specifically, how unexpected the content in a local patch is based on its surround." (2009:3)

The technical details of AIM will not be discussed in this thesis. The interested reader is referred to Bruce & Tsosos (2009) and Bruce (2005). A schematic overview of AIM is presented in appendix D. What is important for this thesis is to understand the output of AIM. Aim takes a visual display and generates a saliency map based on information within the display. Figure x shows the saliency maps in the bottom row for the visual search displays in the top row.

The target in the visual displays is defined by orientation in the top left case, by colour in the top middle and by a combination of the two in the top right. Hotter areas correspond to more salient regions. It is clear from the saliency maps that the visual search of display 3 is the hardest of all. This target does not 'pop out', as is evident from the lack of hot colours for the target on the saliency map. Saliency and therefore *difficulty* of the search task is thus predicted by AIM.

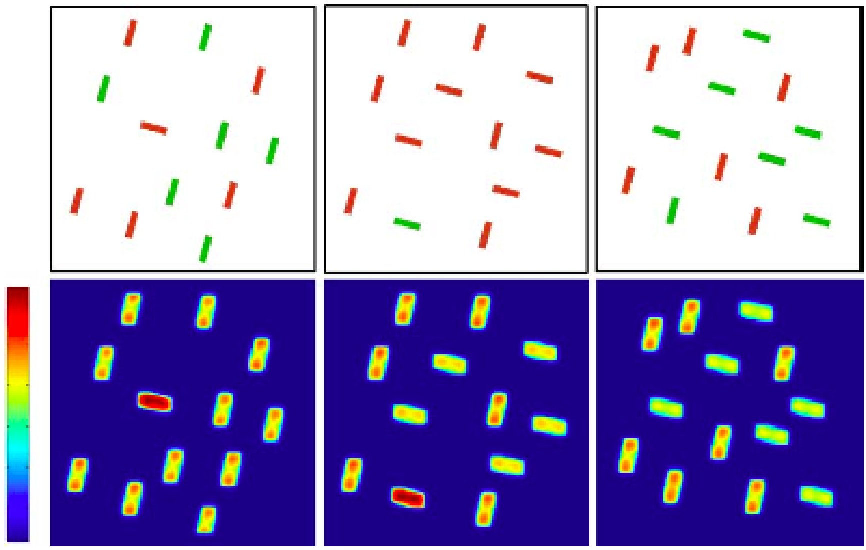

Figure 2. Adopted from Bruce & Tsosos (2009). Three stimulus examples with associated saliency appears in the corresponding maps on the bottom. Hotter areas correspond to more salient regions.

4.2 Research Question

The proposal in this chapter is that visual search tasks have many similarities to the word finding task described in chapters 2 and 3. Although word finding requires a search in long-term memory and visual search requires search of a visual display, in essence both require finding a target amongst more or less similar distractors. Both involve resolving uncertainty, which can be captured by information theoretic means. I therefore hypothesise that individuals with aphasia will show disproportionately more difficulty with a more difficult search task, i.e. using displays in which the target is more similar to its distractors. The research question for this chapter is therefore:

Do people with aphasia show a limitation of processing capacity in processing visual displays with varying complexity?

A visual search task will be presented in which several visual displays with varying saliency maps are used. Based on these saliency maps predictions are made on the performance of healthy and aphasic participants.

4.3 Methods and Materials

4.3.1 Participants

Ten individuals with aphasia that participated in the auditory lexical decision task also performed the visual search task (AD, JH, JJ, JL, LiV, SB, SK, SV and SS). The control group was the same as described in chapter 2 and 3.

4.3.2 Stimulus Materials and Procedure

Visual search displays were created using Matlab. Each display consisted of a number of white circles on a grey background. The target circle (when present) differed from its distractors in size. The displays created contained three crossed factors; set size (9 or 16 items); circle size (target circle 40% or 70% of distractor size) and probe (target present or target absent). There were 20 trials at each unique combination of factors, yielding a session of 160 trials in total. The software package FEP (http://www.hum.uu.nl/uilots/lab/resources.php) was used to create an experimental script to control stimulus presentation and acquired data. The sequence of different displays was randomised within each session. In each session, the participant knew what the target was, but did not know whether a target would be present or absent, or what the display size would be on any trial. Each stimulus was preceded by a beep and 150msec silence. After each stimulus the participant had 10000 msec to respond. 500msec after the response the next stimulus was presented. If the participant failed to respond within the allotted time the next stimulus was presented. The participants performed a binary choice RT task indicating whether a target was present or absent by a button press on each trial. Reaction times were measured from target offset until the button press. Accuracy was automatically recorded. After the practice items participants were given the opportunity to ask questions. Participants were told that they could not correct their response.

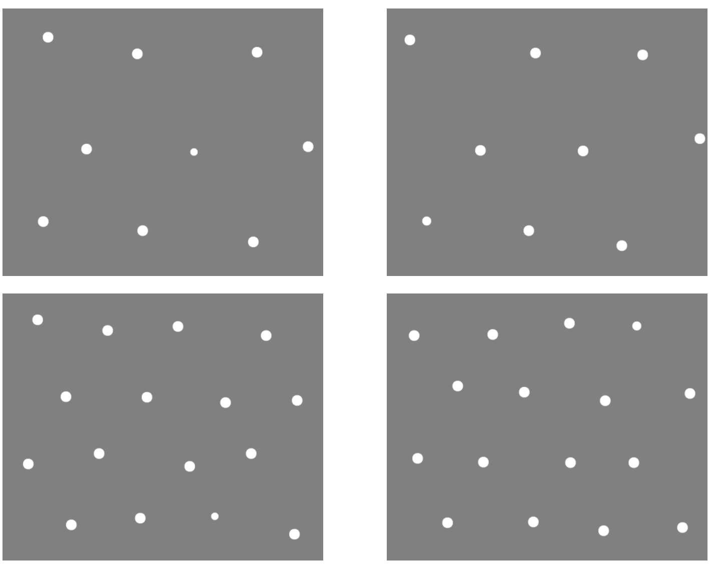

Figure 3. Examples of the search displays with target present. Top two displays with a set size of 9 and bottom two displays with a set size of 16. The displays on the left have the target at 40% of the size of distractors, the displays on the right at 70% of the size of the distractors.

4.3.3 Saliency Maps

Saliency maps were created using AIM (Bruce, 2008). These maps show the saliency of the target items in the visual display and therefore predict which search displays will take more processing. The displays show that increasing the number of distractors (although shown to increase reaction times in visual search) does not change the saliency of the target. However, changing target dimensions and making it more similar to its distractors does influence saliency, as shown by the saliency maps presented below. Hotter areas are more salient regions.

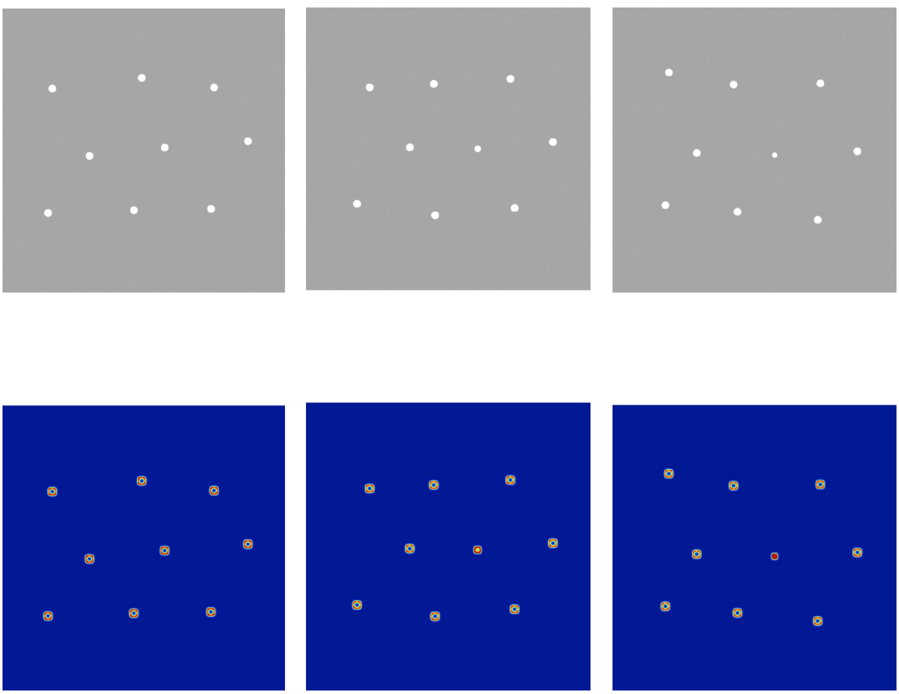

Figure 4a. Three stimulus examples with a set size of 9 items with associated saliency maps. In the left display no target is present; all items have identical saliency. In the middle case, the target is 70% of the size of the distractors. In the right case (the most salient) the size of the target is at 40% of the size.

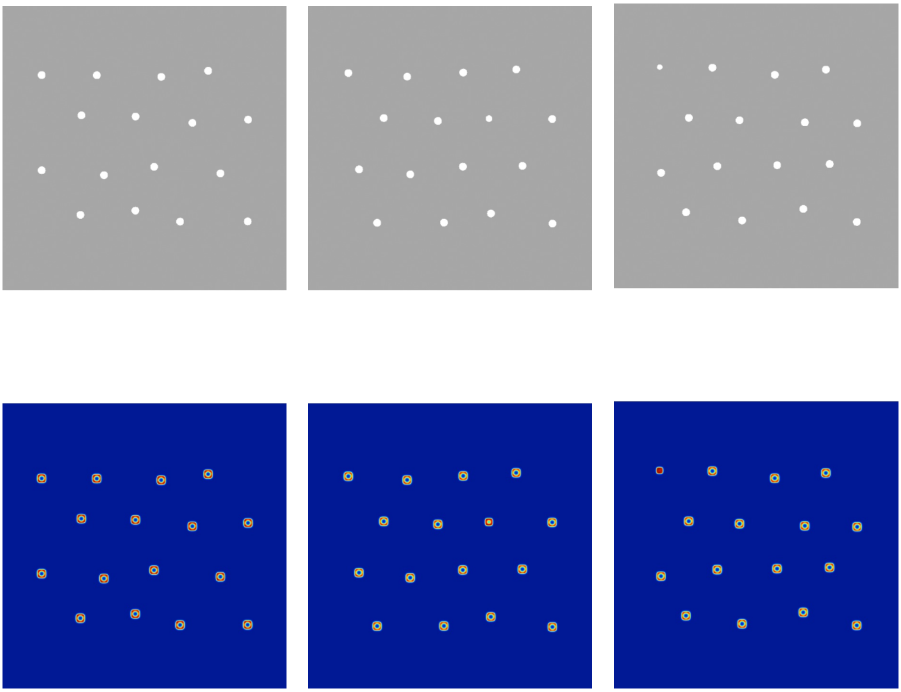

Figure 4b. Three stimulus examples with a set size of 16 items with associated saliency maps. In the left display no target is present, all items have identical saliency. In the middle case, the target is 70% of the size of the distractors. In the right case the target is 40% of the size of the distractors.

4.4 Results

Results were first investigated for error rates. Hits, false alarms, misses and correct rejections are reported in table 1.

	Hits	**False alarm**	**Rejections**	**Misses**
Aphasia	0.95	0.045	0.87	0.12
Control	0.96	0.037	0.93	0.07

Table 1. Hits, false alarms, correct rejections and misses for the visual search task for aphasic and control participants.

T-test revealed no significant differences in error rates between the aphasic participants and healthy controls.

The mean RT data of all trials were analysed using a repeated measures general linear model (GLM), with one between participants factor of group (control or aphasic) and three within subject factors, circle (small versus large target circle), probe (target present or target absent) and display (set size of 9 or 16). For each participant reaction times were averaged for the 20 trials for each particular combination of circle, probe and display. Unless otherwise stated, a significance level of $p<.05$ was adopted for all statistical comparisons.

For the healthy control participants the following effects were found: main effects for presence of target ($F(1,12)=44.511$, $p<0.01$); displays with no target had longer latencies. Display size ($F(1,12)= 34.149$, $p<0.01$); displays with a larger number of items had longer latencies. And circle size ($F(1,12)= 20.984$, $p<0.01$); displays with targets that were less salient (i.e. 70% of distractor size) had longer latencies than those with more salient targets (i.e. 40% of distractor size). Interactions were found between presence of target*display size ($F(1,12)=12.243$, $p<0.05$) and presence of target*circle size ($F(1,12)=1.182$, $p<0.01$).

For the aphasic individuals main effects were found for presence of target ($F(1,7)=25.289$, $p<0.01$); displays with no target had longer latencies. Display size ($F(1,7)=13.047$, $p<0.01$); displays with a larger number of items had longer latencies. And circle size ($F(1,7)=30.323$, $p<0.01$) displays with targets that were less salient (i.e. 70% of distractor size) had longer latencies than those with more salient targets (i.e. 40% of distractor size). Interactions were found for presence of target*display ($F(1,7)=6.885$, $p<0.05$), and presence of target*circle size ($F(1,7)=18.303$, $p<0.05$).

The between subject analysis revealed significant interactions between the within subject factor presence of target*group ($F(1,21)=4.639$, $p<0.05$, df=1); for healthy participants there is a larger effect of presence of target. There was an interaction between display and group ($F(1,21)=5.516$, $p<0.05$); for healthy participants there is a larger effect of display size and for circle size*group ($F(1,21)=4.229$, $p<0.05$), for the aphasic individuals the effect of circle size was larger. There was no main effect of group. Isolated interactions of group x target size and group x display are shown in figure 5.

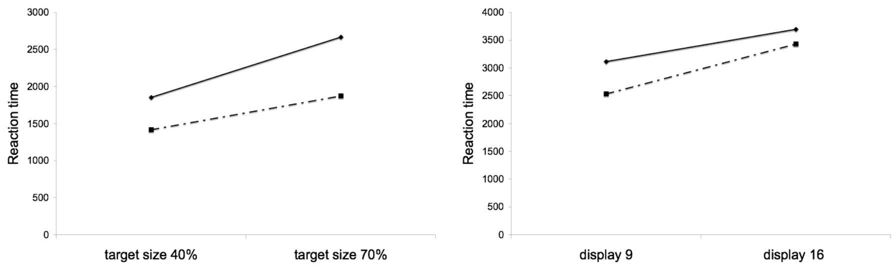

Figure 5. Significant interactions between group x target size (saliency) and group x display size. Dotted lines represent control participants, solid lines aphasic participants.

Further analysis showed that for the easy circle size displays (target at 40% of distractor size) there was no difference in reaction time for the two groups. Furthermore, when the target was absent there was no significant difference between the two groups. An overview of all main effects and interactions is represented in figure 6.

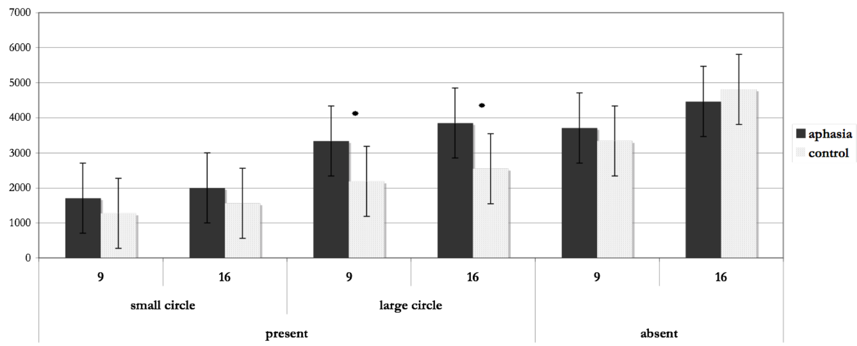

Figure 6. Reaction times for healthy adults and aphasic participants on two display sizes (9 and 16) with target present or absent and with target more (large circle) or less (small circle) similar to its distractors. Significant differences between the groups are starred.

4.5 Discussion

The study presented in this chapter aimed to investigate processing of information in aphasic adults in a non-linguistic task. Unlike previous work on working memory and higher-level attention (sustained and divided), we used a very simple visual search task. We were not so much interested in performance difference overall between aphasic and control participants, but in the extend to which performance would deteriorate for all participants as the complexity of the visual displays was manipulated. We hypothesised that as aphasic adults seem to have difficulties finding a target amongst distractors, they would have significantly more difficulties than control participants when the complexity of the visual display increased. Complexity was manipulated by changing the set size of the display and by varying the size of the target circle; making it more or less similar to the distractor circles. Saliency was then calculated and visualised by saliency maps using a computer paradigm based on information theory.

Reaction times for healthy elderly and aphasic participant were scrutinised for the effect of saliency, set size and presence of a target.

The results show that when no target is present (i.e. all circles are the same) aphasic adults and healthy controls take an equal amount of time establishing that there is no target and to press the corresponding button. This finding shows that it is not the complexity of the task per se that is more difficult for aphasic participants. Further evidence for this comes from the fact that performance is identical for both groups for the easiest displays (i.e. set size 9 and the target very small). The difference in performance occurs when the complexity of the visual displays is changed. Performance of the healthy adults deteriorates significantly more than of that of the aphasic participants when the number of distractor items is increased from 9 to 16. Interestingly, as the saliency maps show, the number of items in the display does not affect saliency of the target. The interaction between group and set size is mainly caused by the poor performance of the aphasic adults on the difficult target size (little saliency) in the easy display of 9 distractors.

Performance of the aphasic individuals is mainly influenced by saliency; the similarity of the target and its distractors. Performance drops significantly when the target is more similar to its distractors, much more so than for the healthy individuals as shown by the interaction between group and circle size. These two interactions (group*set size and group*circle size) show that the aphasic participants show a much stronger detrimental effect of target-distractor similarity (or saliency). The fact that there is no difference between the groups for the easiest condition, nor for no-target condition shows that this difficulty is *not* an effect of poor (sustained or selective) attention.

The results reported in this chapter are in line with the findings reported in the introduction on attention and working memory: although the most characteristic feature of aphasic individuals is their language disorder, difficulties in other cognitive domains are evident. The study in this chapter differed from the studies discussed in the introduction in the experimental design. Complexity of the material was systematically manipulated in order to tease out the specific role of saliency in the processing of (visual) information for the aphasic (and healthy control) participants.

One of the most interesting questions that remains is whether we can directly compare performance on the visual and verbal task. Previous research on the relationship between non-linguistic cognitive and linguistic skills shows that there is hardly ever a direct relation between the two for one individual aphasic patient. Helm-Estabrooks (2002) shows that there mounting evidence that it is impossible to predict the status of nonlinguistic cognitive skills on the basis of language skills. Helm-Estabrooks et al. (1995) found this to be true for 32 patients representing a range of aphasia severity excluding global aphasia. Similarly, Van Mourik et al. (1992) studied only patients with global aphasia and found that cognitive test scores were unrelated to auditory comprehension and that performance on cognitive tasks ranged from relatively spared non-linguistic cognitive performance to the inability to respond at all to testing. Although it proved to be challenging to compare the linguistic and nonlinguistic findings presented in this thesis, the final chapter will provide a discussion on the relationship between the findings of this chapter and those of chapters 2 and 3.

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PART B: SPONTANEOUS SPEECH

Part A of this thesis provided an experimental approach to reduced processing capacity in aphasia within an information-theoretic framework. In chapter 2 I showed that information load and inflectional entropy reliably affect latencies of young and healthy elderly people. Although minor differences in performance for the auditory lexical decision task did occur between the two groups, there was no interaction between any of the within-subject factors and group, indicating that the process of word recognition does not change significantly with age. In chapter 3 I compared performance on the same auditory lexical decision task between aphasic participants and elderly control participants. The aphasic participants had no difficulties performing the lexical decision task; performance was well above chance. Furthermore the results showed that frequency and number of synsets affected latencies to the same degree for both groups. These findings indicate that the lexical representations are still present in the lexicon for the aphasic individuals, i.e. the lexicon has not degraded to the extent that lexical entries have gone missing. Furthermore, a dense semantic network (as measured by the number of synsets) aids word recognition to the same degree for both groups, indicating that the neuronal circuits between words are intact.

Both groups did significantly differ in how their latencies were affected by the information theoretic measures. I interpreted these findings to show that although overall organisation of the lexicon is intact, distinguishing the target form between other forms within the inflectional paradigm is significantly harder for aphasic speakers. Chapter 4 provided evidence that this difficulty of distinguishing targets from distractors is also present in non-verbal tasks, such as visual search. Processing capacity thus seems to be reduced in aphasic individuals, specifically processing that is required to resolve uncertainty in selecting a target (a lexical form or a visual target) from its distractors.

Part B sets out to find out whether we can find more evidence for this hypothesis by investigating spontaneous speech data. Two further applications of information theory are introduced to allow us to investigate processing capacity in aphasia. The first chapter, chapter 5, presents an analysis of complete samples of spontaneous speech of four aphasic speakers. The second chapter, chapter 6, provides a comparison between aphasic speakers and children with a specific language disorder and specifically focuses on the production of articles in spontaneous speech.

5 ENTROPY AND ZIPF'S LAW IN APHASIA[4]

In the previous two chapters an experimental design was used to investigate processing of verbal items in aphasia. It allowed for specific predictions of performance by manipulating two information theoretic measures: information load and inflectional entropy in an auditory lexical decision task. In chapter 3 I showed that many of the factors affecting latencies in lexical processing are the same for people with and without aphasia (number of synsets, frequency), indicating that the structure of the mental lexicon seems unchanged in aphasia. However, the effect of two information theoretic measures did significantly differ for both groups. Inflectional entropy showed a facilitatory effect on latencies, as it did for the healthy controls, but the effect was diminished. Information load did not correlate to reaction times for the aphasic participants. These two findings both suggest that although the overall structure of the mental lexicon is unchanged, processing is different. In chapter 3 I argued that the ability to resolve uncertainty and to distinguish a target between distractors in the mental lexicon in aphasia is reduced. In the current chapter I set out to find more evidence for the claim that processing of information is reduced and that this leads to difficulties selecting target words in aphasic speech. This chapter discusses the use of a different application of information theory: the relation between Zipf's law and entropy. Looking at complete speech samples (not just verbs) I will show that the overall organisation of the mental lexicon in aphasia is intact but that due to reduced processing capacity aphasic speakers have difficulty accessing words efficiently.

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[4] The study described in this chapter was a joint project with Marjolein van Egmond. Results have been published previously as van Egmond, van Ewijk & Avrutin (2011). A new theoretical model for word-finding difficulties in aphasia. *Procedia-Social and Behavioural Sciences*, 23, 175-176.

5.1 Introduction

5.1.1 Zipf's Law

Zipf's law is one of the most common and well-known power laws in the natural world. Using written texts, George Zipf (1965) showed that given some corpus of natural language utterances; the frequency of any word is inversely proportional to its rank. In other words the most frequent word (rank 1) in a text will occur approximately twice as often in a text as the second most frequent word (rank 2), three times more often than the third most frequent word (rank 3), etc. This is modelled by the power function [1]:

[1] $P(f) \sim \mathrm{f}^{-\beta}$

where p(f) is the proportion of words whose frequency is f in a given sample text and ß>0. When plotting the data on a log-log scale there is a lineair dependency between rank and frequency (as shown in graph 1).

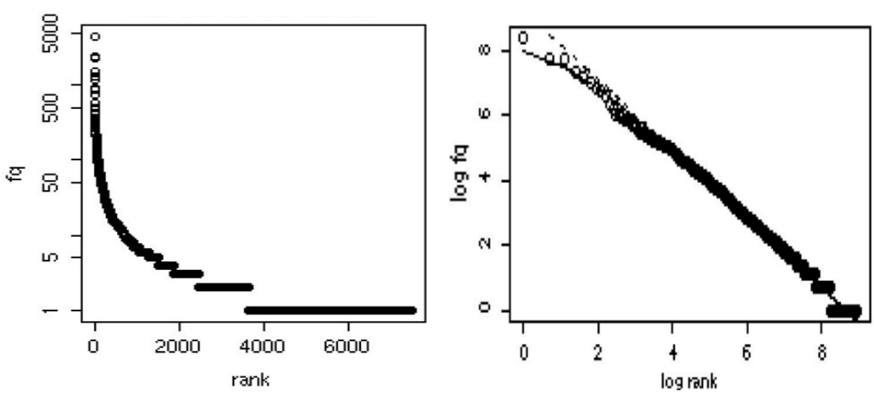

Figure 1. Zipf's law in H.G. Wells, *The War of the Worlds* (1889) (taken from Baroni, 2008). On the left a rank/frequency plot on a linear scale, on the right the same rank/frequency plot on a log-log scale.

Zipf's law has been shown to occur in many ratings, some of which are unrelated to language. Examples are populations in city sizes, firm sizes in industrial countries and family names (e.g. Corominas-Murtra & Solé, 2010; Dahui, Menghui & Zengru, 2005). The crucial question of course is *why* Zipf's law occurs. In his 1965 book Zipf argues that the law occurs as a result of the Principle of Least Effort; a broad theory that postulates that people (and animals) will naturally choose the path of least resistance, or effort. The distribution of word use then is due to the desire to communicate efficiently with least effort. Zipf does not explain exactly how this process affects language, but in recent years Ferrer i Cancho and colleagues have further explored this line of work. Ferrer i Cancho & Solé (2003) show, using a mathematical model[5], that Zipf's law is the outcome of the nontrivial arrangement of associations in a lexicon that has to comply with hearer and speaker needs. In order to reduce effort it would be preferential for the speaker to use as few different words as possible to express a message (unification), whilst the listener would prefer a different word for every meaning (diversification). Theoretically, speaker effort is minimal if one word is used to express all meanings, whilst hearer effort is minimal if every meaning is expressed with a different word, as this would minimize ambiguity. Zipf's law arises as a result of the tension between these two needs.

Zipf's law was originally thought to reveal principles of natural language functioning, but this has given rise to a large body of criticism (Miller & Chomsky, 1963; Mandelbrot, 1953; Li, 1992). The critics major claim is that the statistics of simple random sequences of characters - including a special one that behaves as a word delimiter - reproduces Zipf's law for word frequencies. Recently however Ferrer i Cancho & Elvevåg (2010) have convincingly argued that frequency distributions of random texts do not resemble the frequency distributions of natural language. For this, they compared ten random texts

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5 More details of this model are provided in Section 5.1.2.

generated by different processes to ten English texts. They performed rigorous statistical fitting to the data and compared the consistency of ranks from real texts and those of random texts of the same length. Using three different rank statistics they show that the real and random texts are statistcally inconsistent in all cases. Specifically, the real rank statistic is smaller than expected for a random text. Zipf's law does not therefore result as an arbitrary process of creating word lists, but is a fundamental characteristic of natural language.

5.1.2 Zipf's Law and Information Theory

The balance between effort of communication and Zipf's law has been investigated in an information theoretic paradigm by Ferrer i Cancho and colleagues. As discussed in previous chapters, according to Shannon's standard theory the goal of communication is to maximize information transfer. However, information transfer requires effort, or cost. To express the cost of communication Ferrer i Cancho et al. use Shannon's entropy (H):

[2] $$H(X) = -\sum_{i=1}^{n} p(x_i) \log p(x_i)$$

for which a high H corresponds to a high the cost of communication.

In order to model entropy (H) Ferrer I cancho and colleagues propose a model of communication in which signals from a set S are used to communicate about stimuli from a set R. Signals are equivalent to words and stimuli are the basic ingredients for word meaning. In this model the lexicon is represented by a system involving a set of n words S = {s1, …, si, …, sn} and a set of m objects of reference or meanings R = {r1, …, rj, …, rm}. The interactions between words and their meanings can be represented by a binary matrix A = {aij} (with 1 ≤ i ≤ n and 1 ≤ j ≤ m), with signals as columns and rows as words. Each column represents a word; all words together are called set S. This set of n words S = {s1, …, si, …, sn} represents the phonological form. Each row represents a basic ingredient for word meaning, which are called objects of reference or simply objects. All objects together are called set R. This set of m objects R = {r1, …, rj, …, rm} represents the logical form. A cell contains a 1 if a word is associated to an object. Otherwise, it contains a 0. Every word has to have at least one meaning, and synonymy is allowed. An example of part of such a matrix is given in table 1.

	Word 1	Word 2	Word 3	Word 4	Word..	Word n
Obj. a	1	1	0	0	0	0
Obj. b	1	0	0	1	0	1
Obj. c	1	0	1	0	1	0
Obj. d	0	1	0	1	0	0
Obj. e	1	0	1	0	0	0
Obj. f	1	1	0	0	0	0
Obj. g	1	0	0	0	0	0
Obj. …	0	0	1	0	0	0
Obj. m	1	1	0	0	0	0

Table 1. Example of a matrix that represents the lexicon

Based on this model, the probability of a word $p(s_i)$ is defined as the sum of the probabilities of that word and each of its meanings occurring together:

[3] $$p(s_i) = \sum_j p(s_i, r_j)$$

The probability of a word and its meaning occurring together is (according to Bayes theorem):

[4] $$p(r_j, s_i) = p(r_j)p(s_i \mid r_j)$$

Here, $p(r_j \mid si)$ is defined as 1 divided by the number of synonyms for each object to which it refers:

[5] $$p\left(r_j, s_i\right) = a_{ij}\frac{1}{w_j}$$

The cost of communication (entropy (H)) is then based on probability distributions of frequencies to calculate uncertainty or predictability of a system (or technical message in its original form). Entropy is at maximum if all elements in a set have equal probabilities. In terms of the lexicon, if all words have equal frequencies, entropy of the set is at a maximum. In contrast, when a word has a probability of 1 and all others words therefore have a probability of 0, entropy is 0. H(S) therefore is a measure of the cost of signal use. The higher H, the higher the cost of communication. As the goal of communication is to maximize information transfer whilst keeping cost at a minimum, Ferrer i Cancho and colleagues propose that the any biological communication system is captured by the function[6]:

[6] $$\Omega = I\left(S,R\right) - H\left(S\right)$$

The function is a combination of the goal of communication, that is, maximizing the information transfer between the set of signals and the set of stimuli, I(S,R), and the constraints imposed by the biology of the communication system, which tend to minimize H(S), the entropy associated with signals.

[6] NB A simplified version of the function Ω is used here. Ferrer i Cancho include a constant, λ, where where $0 \leq \lambda \leq 1$. λ is a parameter controlling the balance between −I(S, R) and H(S) and specifies the goal of communication. When $\lambda = 0$ the goal of communication does not matter at all and the same happens to the constraints of communication when $\lambda = 1$.

Ferrer i Cancho assumes that a word is used with a frequency that is proportional to its number of stimuli[7] and shows that Zipf's law (based on word frequency) is the outcome of the balance between maximizing information transfer whilst minimizing H(S), and that in human language ß≈2. A similar balance between chaos and order was also shown by Corominas-Murtra & Sole (2010).

5.1.3 Zipf's Law in Populations with Reduced Processing Abilities

Although the previously discussed papers on Zipf's law and entropy investigated the balance between maximisation of information transfer and the cost of communication, imposed by limitations of the human brain, application to populations with possible reduced cognitive processing abilities is sparse. Ferrer i Cancho (2006) discusses a few populations and type of texts in which ß deviates from the typical value of 2. Speech of adults suffering from schizophrenia shows large ß values in the acute stages of the illness (Piotrowski et al., 1994). In this stage, verbal output reflects the disturbance in organisation

[7] It is important to note that Ferrer i Cancho (2005) assumes that word frequency and the number of meanings that word is associated to are positively correlated. These associations should be taken broader than meanings. Take for example the verb *to write*. The meaning of this verb only includes the action of writing itself. However, this word is also associated to the meanings of words like *pencil*, *paper*, *letter*, *book*, *writer* etc, which he calls 'stimuli'. All these stimuli together make up the complex meaning of the verb *to write*. Ferrer i Cancho assumes that the more stimuli a word is associated to, the higher the probability of using that word. In this framework number of associations and frequency can be assumed to be highly correlated. This is why, when calculating I and H, number of associations and frequency are used interchangeably. Although Ferrer I Cancho and colleagues argue that number of meanings and frequency are correlated and therefore the stimuli in his model are also positively correlated to word frequency, simply equating number of stimuli in the model with frequencies in the real world is a big (and possibly incorrect) leap. A more accurate and detailed account for the relation between Ferrer I Cancho's model of the lexicon and real lexical data is currently being explored by van Egmond (2011). For the purpose of this chapter we will assume that entropy and Zipf's law are strongly interlinked and that Zipf's law occurs as a balance between minimizing entropy whilst maximising information transfer.

and coherence of thoughts and an incapability to adjust to the needs of the hearer. Speech is therefore much decreased in coherence and difficult to comprehend for the listener, leading to larger ß values when applying Zipf's law. Young children's speech as well as the speech of children with Down's syndrome on the other hand has been shown to have a reduced ß, typically of approximately 1.5 (Ferrer i Cancho, 2005; Piotrowski & Spivak, 2007). The authors speculate that children, due to brain limitations, might not be able to overcome the cost of communication as in normal adult speech. They (unknowingly) balance communication towards saving the cost as much as possible, in other words keeping H to a minimum.

The literature discussed so far shows that Zipf's law is a fundamental property of natural language. It has been shown to be evident in natural language and not in random texts and appears to reflect the organisation of the mental lexicon in balancing cost of communication and information transfer during communication. Only a handful of studies have attempted to investigate Zipf's law in pathological populations. These show that for individuals with schizophrenia and young children (with Down Syndrome) Zipf's law holds, but slopes of the curve might deviate from the typical value found for healthy adults. For young children this difference in slope has been explained by their inability to overcome cost of communication and therefore unknowingly reducing entropy of the system. As far as we know, no one has investigated whether Zipf's law holds for (non-fluent) aphasic speech and if so whether differences are found between aphasic speech and healthy adult speech. This current chapter sets out to do exactly that. The research questions for this chapter are therefore:

1. Does the frequency spectrum of spontaneous speech produced by aphasic individuals obey Zipf's law?
2. If so, does the slope of the curve differ from what is usually found in speech produced by healthy, intact language users?

As we have seen in previous chapter, processing is reduced in aphasic individuals and they are less capable resolving uncertainty (or entropy). We therefore hypothesise that if Zipf's law does uphold, ß will be reduced in aphasia, due to their inability to overcome H as healthy adults do. In the next sections we investigate Zipf's law for 4 samples of aphasic speech.

5.2 Methods and Materials

5.2.1 Participants

Four aphasic speakers were recruited. Participants JvdH and PH were recruited from Afasiecentrum Tilburg,; EvdL and JJ were recruited from Samen Verder in Tilburg. All patients were diagnosed as non-fluent by speech therapists. All patients were at least 3 years post stroke. Details of the aphasic speakers are given in table 2.

As a control group, four healthy speakers were selected from the Corpus Gesproken Nederlands (CGN, Nederlandse Taalunie, 2004). They were matched on gender with the aphasic speakers. Two recordings were chosen: fn000260 and fn000276. Both recordings contained spontaneous conversations of two people of sufficient length, each of which provided a match with one of the aphasic speakers. Recording fn000260 contained speech from the speakers N01004 and N01005; recording fn000276 contained speech from the speakers N01010 and N01011. Speaker details are given in Table 2.

	Time post onset	Cause	Type of aphasia
EvdL	10 year, 4 months	Stroke	non-fluent
JJ	7 year, 3 months	Multi-infarct syndrome	non-fluent
JvdH	6 year, 3 months	Stroke	non-fluent
PH	3 year, 10 months	Stroke after trauma	non fluent

Healthy speakers			Aphasic speakers		
Speaker	Sex	Age	Speaker	Sex	Age
N01011	female	25-34	EvdL	female	59
N01005	female	56 or older	JJ	female	63
N01004	female	25-34	JvdH	female	36
N01010	male	25-34	PH	male	33

Table 2. Control & aphasic speaker details. The CGN only provides an age range, not the exact age at the time of recording.

5.2.2 Procedure

Spontaneous speech from aphasic participants was obtained through interviews with the author or a student assistant, which lasted for about 20 minutes per participant. These interviews took the form of informal conversations, which means that interviewers actively participated in the conversation.

5.2.3 Analysis

All interviews with the aphasic participants were recorded on video. They were orthographically transcribed using the CHAT-format and labelled for part of speech. The CHAT-format is part of the CHILDES project (MacWhinney, 2000). This format allows for automatic searches and analyses by means of the accompanying CLAN programs. The speech fragments that were selected from the CGN were manually converted from PRAAT-format to CHAT-format. Analysis was performed over all words, but also over content words only (as the aphasic speakers typically have difficulty with function words). For all speakers, the first 102 content words (nouns, verbs, adjectives and adverbs) were selected for analysis. This number is equal to the number of content words in the smallest sample (EvdL). Details about the statistical analysis that was performed will be provided in the results.

Estimation of the parameters of Zipf's law is not straightforward. Linear regression in log-log space can lead to a highly biased estimation of the exponent if data points do not follow a normal distribution (Ferrer i Cancho, personal communication). One way to circumvent this problem is by studying the frequency spectrum instead of the frequency distribution, of which an example is given in figure 3. The frequency spectrum shows the number of types V(m,N) in each frequency class, where a frequency class is the number of words occurring exactly m times in a sample of N words in total (Baayen, 2001: 10). This means that the group of data points for each frequency is reduced to one data point per frequency class. As a result each frequency class is assigned equal weight, which is not the case for the frequency distribution where lower frequency classes receive more weight due to the larger number of data points in these classes. In what follows, Zipf's law will therefore be examined through frequency spectra instead of frequency distributions.

5.3 Results

The frequency distribution of healthy speakers and aphasic speakers as plotted on a log-log scale is given in figure 2. Visual inspection of this distribution shows that the data closely follow a straight line, indicating that Zipf's law applies.

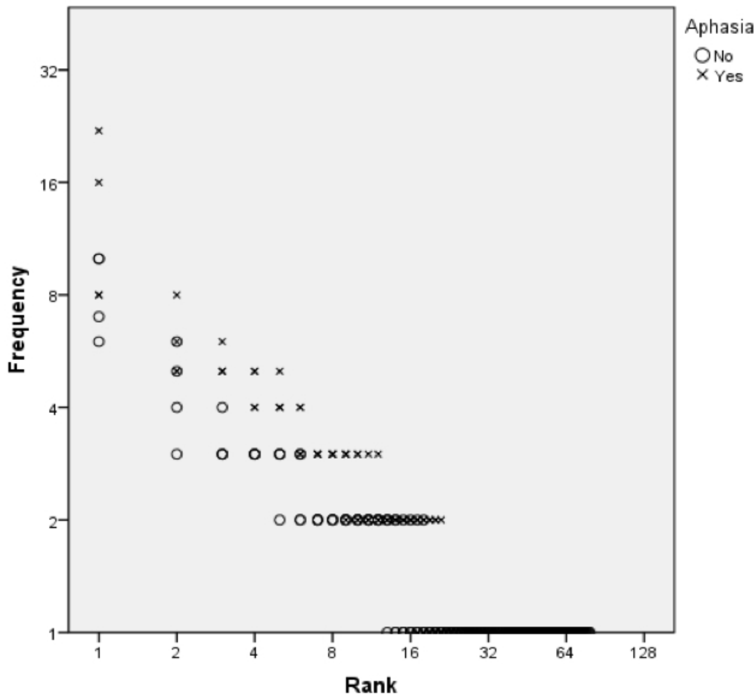

Figure 2. Frequency distribution of all words in the samples of the aphasic speakers (the crosses) and healthy controls (circles)

Next, the frequency distribution was converted into a frequency spectrum. This involved a severe data reduction: The participant data were reduced from 102 data points to on average six data points per participant. The group data were reduced from 408 to 20 (healthy speakers) or from 408 to 25 (aphasic speakers) data points. This reduction causes only highly significant effects to surface.

Both frequency classes and V(m,N) were transformed to their logarithms. Only frequency classes in which words were present were included in the data, i.e., empty frequency classes were excluded.

The frequency spectrum, shown in figure 3, shows a straight line with a negative slope when plotted in log-log 2-dimensional space. For both groups, frequency class is a significant predictor of the size of the frequency class. The model provides a good fit of the data: R^2 for aphasic speakers is 0.888; R^2 for healthy speakers is 0.859. Notice that the data points do not need to follow a negative sloping line: for example, different frequency classes could have had equal sizes, which would have resulted in a non-sloping line. This negative sloping line shows that Zipf's law applies.

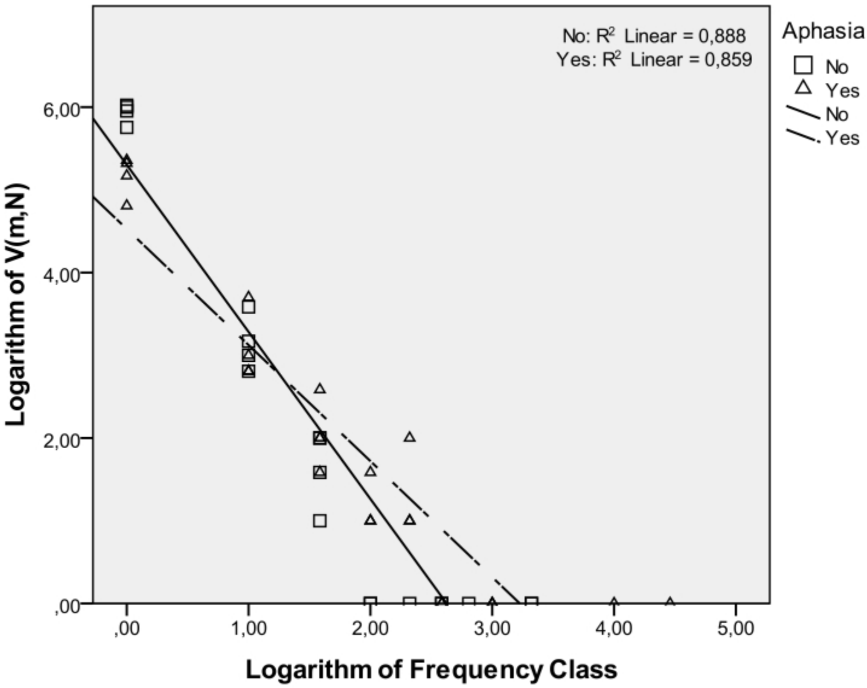

Figure 3. Frequency spectrum for the aphasic and elderly samples. Squares represent aphasic data points, triangles control data points. The solid line represents the regression line for the aphasic individuals, the dotted line the regression line for control participants.

For each speaker, frequency rank is a significant predictor of the size of the frequency class. For all speakers, $R^2 \geq 0,830$ which indicates a good fit of the model. Even though these findings are expected if Zipf's law applies, it is no obvious finding: sample sizes were very small after the transformation from frequency distributions to frequency spectra. Group differences were investigated using an exact Fisher randomisation test and whos that for content words, beta is significantly lower for the aphasic speakers than for matched controls. For the complete sample there is a trend in this direction (*p*=0.057). Details about slope values and their statistical significance are given in table 3. A visual representation of slope values with their standard error ranges is given in figure 4. In all cases the slope is negative: for every speaker low frequency classes were largest while high frequency classes were smallest.

	BETA		All Categories							Content Words						
			Types	Tokens	N	Beta	95% CI min	95% CI max	r^2	Types	Tokens	N	Beta	95% CI min	95% CI max	r^2
Same Sample Size	Aphasic speakers	EvdL	104	386	15	**1,084**	0,706	1,462	0,747	45	102	7	**1,140**	1,733	0,547	0,830
		JJ	147	386	12	**1,370**	0,912	1,828	0,816	62	102	6	**1,865**	2,450	1,279	0,951
		JvdH	138	386	16	**1,313**	0,999	1,627	0,852	56	102	7	**1,802**	2,193	1,412	0,966
		PH	96	386	15	**0,933**	0,595	1,271	0,733	56	102	5	**1,216**	1,945	0,486	0,904
	Healthy speakers	N01011	169	386	14	**1,710**	1,433	1,988	0,938	79	102	4	**2,121**	3,119	1,124	0,977
		N01005	170	386	11	**1,136**	0,559	1,713	0,688	76	102	5	**1,821**	3,123	0,520	0,869
		N01004	152	386	13	**1,476**	1,067	1,885	0,851	75	102	5	**2,827**	3,322	0,332	0,834
		N01010	156	386	15	**1,551**	1,308	1,793	0,936	72	102	6	**2,448**	3,162	1,734	0,958
			Exact Fisher randomization test: p = 0,057							*Exact Fisher randomization test: p =* ***0,029***						
Full Sample Size	Aphasic speakers	EvdL	135	611	18	**1,056**	0,750	1,361	0,770	80	267	11	**0,985**	0,582	1,389	0,772
		JJ	147	386	12	**1,370**	0,912	1,828	0,816	87	151	7	**1,706**	1,180	2,233	0,933
		JvdH	307	1583	31	**1,096**	0,905	1,287	0,826	222	726	18	**1,231**	0,949	1,513	0,843
		PH	189	1084	25	**0,818**	0,534	1,103	0,606	139	377	14	**1,412**	0,985	1,839	0,813
	Healthy speakers	N01011	349	1117	25	**1,335**	1,032	1,638	0,783	266	490	12	**1,677**	1,094	2,261	0,804
		N01005	258	761	19	**1,117**	0,733	1,500	0,689	177	302	10	**1,646**	0,761	2,532	0,697
		N01004	475	2086	34	**1,106**	0,884	1,328	0,763	371	918	20	**1,325**	0,993	1,658	0,796
		N01010	430	1560	29	**1,286**	1,072	1,500	0,849	341	709	14	**1,752**	1,368	2,136	0,892
			Exact Fisher randomization test: p = 0,200							*Exact Fisher randomization test: p = 0,057*						

Table 3. Slope values and their statistical significance for the speech of aphasic and healthy speakers. The calculation of alpha is based on the average rank per frequency. N=number of datapoints on which the calculations are based. Average rank per frequency class for the calculation of alpha and frequency class size per frequency for beta.

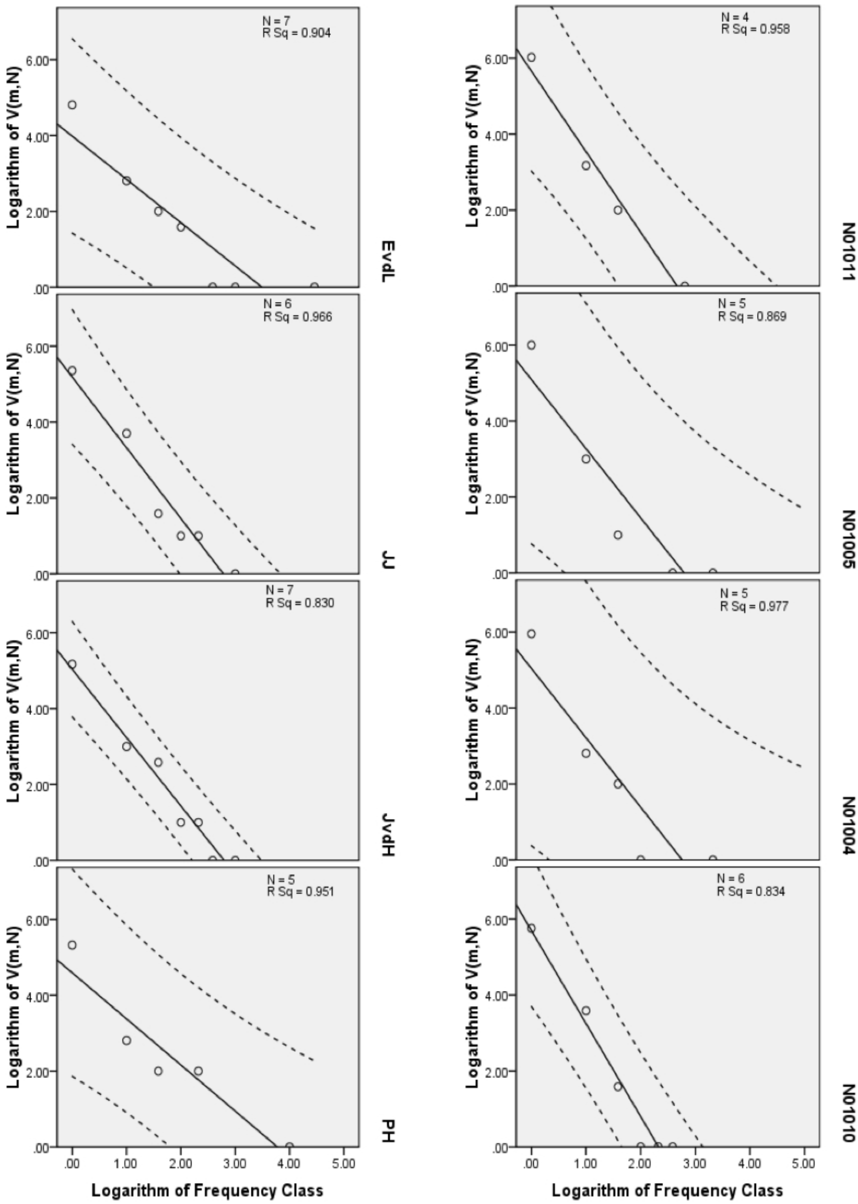

Figure 4. Frequency spectra per participant, on the left panels aphasic participants, on the right the control participants.

5.4 Discussion

The current chapter set out to investigate reduced processing in aphasia by examining the presence and shape of Zipf's law in people with aphasia. As discussed in the introduction, Zipf's law has been suggested to result from the balance between maximisation of information transfer and minimisation of effort of this communication. Specifically, the balance between the goal of communication, that is, maximizing the information transfer between the set of signals and the set of stimuli, I(S,R), and the constraints imposed by the biology of the communication system, which tend to minimize H(S), the entropy associated with signals (Ferrer i Cancho, 2005).

The first research question of this chapter was whether Zipf's law would uphold in aphasic speech. We found that language generated by these four patients obeys Zipf's law. This may seem trivial, but is actually quite remarkable if one considers the level of impairment of some of the aphasic participants. It was argued in the introduction that Zipf's law follows as output of a complex system, in this case the lexicon. The current finding that aphasic speech conforms to Zipf's law therefore suggests that the basic organisation of the lexicon is the same for both groups. This finding is in line with theories asigning aphasic word finding difficulties to lower processing rates rather than defects of the system. Lower processing rates would result in a relative preference for words that are easier to access but would not result in severe disruptions of frequency relations. The current results show exactly this.

The second research question involved the slope of Zipf's curve. Sparse previous research has shown that this curve may deviate for pathological groups, such as children with Down's syndrome and adults suffering from schizophrenia. Zipf's curve has also been shown to have a reduced slope for typically developing young children. Ferrer i Cancho (2005) suggests that this group of speakers with ß < 2 is constrained by the cost of communication more than healthy adult speakers. In other words, if we look at the function for Ω which was presented in the introduction and repeated here:

[6] $$\Omega = I(S,R) - H(S)$$

young children's ability to overcome the cost of communication (H(S)) is reduced. The outcome of the balance between maximizing information transfer whilst minimizing H(S) is therefore different for this group which leads to a more shallow slopen of Zipf's curve. Ferrer i Cancho argues that for young children this is probably due to capacity limitations of their maturing brain.

Previous research on aphasia has shown that processing of (linguistic) information is reduced in aphasia. We therefore hypothesised that, similar to the findings for very young children, the curve (measured by beta) would deviate from that found in healthy speakers. Our results confirm this hypothesis. Slopes for our four individuals with aphasia were significantly less steep than those of the matched controls. In other words, although Zipf's law still upholds, the balance between I (information transfer) and H (cost of communication) has shifted. We propose that although the structure of the lexicon is unchanged in people with aphasia, they are unable to process the same level of H as adults with a healthy brain. Their ability to resolve uncertainty in the lexicon is reduced. The exact relationship between Zipf's law and Ferrer i Cancho's model of the lexicon and entropy within the lexicon are currently under investigation by van Egmond (cf. van Egmond, van Ewijk & Avrutin, 2011).

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6 ARTICLE OMISSION IN CHILDREN WITH SLI AND ADULTS WITH APHASIA[8]

6.1 Introduction

The current chapter explores a third information theoretic measure in explaining spontaneous speech data. Previously I showed that for aphasic adults ease and speed of retrieval of an inflected verb is dependent on the complexity of its paradigm as measured by the information theoretic measures information load and inflectional entropy. I showed that these factors, although similar in direction for healthy adults and aphasic speakers are different in strength for both groups, indicating that the aphasic adults may not have sufficient resources to process information in real time. In chapter 5 I further supported this view by investigating Zipf's law and its relation to entropy for a small group of healthy and aphasic adults. Again I showed that, although the lexicon appears intact and Zipf's law holds for the spontaneous speech of this group of language-impaired individuals, there is a difference in the slope of the curve of Zipf's law. This was interpreted as a reflection of an inability to balance the cost and goal of communication as efficiently as unimpaired individuals. In the current chapter a third information theoretic measure is used to investigate another difficulty frequently seen in aphasic speech, the production of articles. I will use a method that has previously been used to explain cross-linguistic differences in acquisition rates of articles for young typically developing children to further explore the use of information theoretic measure in the field of language disorders and specifically to investigate possible processing difficulties. In addition to the spontaneous speech of 12 aphasic adults, I will investigate the speech of 12 children with specific language

[8] A version of this chapter reporting only the data for the SLI group has been published as van Ewijk, L and Avrutin, S. (2010). Article omission in Dutch children with SLI: A Processing Approach. *Entropy*, 12(4), 798-817.

impairment (SLI). As the method proposed has so far only been explored for healthy young children (de Lange, 2008), I wanted to explore the use of this method for a language disordered group that is also in the process of language acquisition and compare this to the results of the aphasic individuals. As discussed in more detail below, both aphasic individuals and children with SLI have been shown to have similar difficulties with the production of articles (cf. Bedore & Leonard, 2001 for SLI and Ruigendijk & Bastiaanse, 2002 for aphasia) and the question arises whether this difficulty might be due to a similar underlying (processing) problem.

6.2 Research Question

To what extent can limitation of information processing capacity as measured within an information theoretic paradigm explain the article retrieval difficulties of Dutch children with Specific Language Impairment?

A short introduction on SLI will be provided in the next section, after which literature on difficulties with article production for both groups will be discussed. A framework for article production in general will be provided and a detailed description of the proposed information theoretic measure.

6.3 Background

6.3.1 Specific Language Impairment

Specific Language Impairment (SLI) is a heterogeneous disorder that impairs language acquisition in children with no obvious cognitive, emotional or social difficulties. Diagnosis of SLI is primarily based on a discrepancy criterion, first suggested by Stark & Tallal (1982). The ICD-10 (WHO, 1993) criteria for example specify that language skills be at least one SD below non-verbal IQ. The incidence of SLI in kindergarten has been estimated to be around 7%

(Tomblin et al., 1997) and in specialised class units, up to 13% (Archibald & Gathercole, 2006).

Although children with SLI show difficulties in all aspects of language, grammatical morphology has often been described as particularly weak in these children (e.g. Bishop, 1992; Leonard & Bortolini, 1998). One of the hallmarks of SLI is the omission or substitution of free and bound grammatical morphemes. Tense marking has been shown to be particularly difficult and for English low levels of accuracy in the set of tense morphemes (-s third person singular, *-ed* regular past, *BE,* and *DO*) has been suggested as a clinical marker for this disorder (Rice & Wexler, 1996).

Many theories have been proposed to explain the difficulties these children experience with morphosyntax. They can broadly be divided into two categories: linguistic theories claiming that some linguistic information in these children is underspecified or impaired (e.g., Implicit Rule Deficit (Gopnik & Crago, 1991); Extended Optional Infinitive Account (Rice & Wexler, 1996)). On the other hand there are processing theories that suggest that the linguistic knowledge for these children is intact, but that they struggle using it due to reduced processing abilities (e.g., Auditory Processing Deficit (Tallal et al., 1996); Generalised Slowing Hypothesis (Kail, 1994); Surface Account (Leonard, Eyer, Bedore & Grela, 1997; Leonard, McGregor & Allen, 1992)). In the last two decades, a fair number of studies have been dedicated to a specific subset of grammatical morphemes: the production of articles. Although the pattern and performance on production of articles varies across languages, a weakness in this area is evident for all children with SLI, regardless of the language they are acquiring (provided the language has articles in the first place).

6.3.2. Article Production in Aphasia

In addition to the well-known impairment in verbs and verb finiteness, one of the hallmarks of (non-fluent) aphasia in languages such English and Dutch is the relatively low number of closed class elements such as determiners and pronouns in speech production (see, among others de Roo, 1999; Ruigendijk, 2002). Within the group of determiners, omission and substitution of articles by agrammatic speakers has been described more specifically for Dutch and German by Havik & Bastiaanse (2004), De Roo (1999), and Ruigendijk & Bastiaanse (2002). In Swedish it has been shown (Månsson & Ahlsén, 2001) that non-fluent aphasic speakers more often omit indefinite articles than definite articles. However, in addition to the obvious difference in definiteness for the two groups of articles, there are also morphological differences between the two in Swedish: the indefinite article occurs as a free grammatical morpheme, as in e.g., English, Spanish and Dutch. Whereas the definite article is marked by a suffix added to the noun. It could therefore very well be that the differences in performance on definite and indefinite articles in Swedish aphasia have a morphological aetiology and have little to do with definiteness per se. Havik & Bastiaanse (2004) therefore investigated the role of definiteness in Dutch article production, a language in which both definite and indefinite articles are freestanding morphemes. The Dutch articles system is presented in table 1.

	Definite		**Indefinite**	
Gender	**Common**	**Neuter**	**Common**	**Neuter**
Singular	*de*	*het*	*een*	*een*
Plural	*de*	*de*	-	-

Table 1. Morphosyntactic forms of the Dutch articles.

Analyses of the speech from a semi-structured interview with 8 agrammatic speakers showed that around 45% of the articles were produced correctly. By far the most common error was that of omission, with a few gender substitutions. For these Dutch patients, Havik & Bastiaanse found no significant differences between definite and indefinite articles. Definiteness therefore does not seem to play a role in the omission patterns in (Dutch) aphasia (but cf. Ruigendijk & Baauw, 2010 for findings on Dutch more similar to those in Swedish). It is clear, however, that in Dutch (and many other languages) determiners and articles in particular provide a challenge for people with (non-fluent) aphasia.

6.3.3 Article Production in SLI

Looking at the production of functional categories in English children with SLI, Leonard (1995) found that they produce fewer grammatical elements than language-matched younger peers. With regards to article production, they found that all of their ten 3–5 years old children with SLI did produce articles, but significantly less often than the language matched group. In a cross-linguistic study on French and Italian, Le Normand, Leonard & McGregor (1993) found that French preschoolers with SLI show similar rates of omissions of articles as their language matched peers and have significantly fewer difficulties than their group of Italian children with SLI. Language matching was based on mean length of utterance (MLU), a standard matching criterion in language acquisition research. Leonard Bortolini, Caselli, & Sabbadini (1993) investigated the use of the definite article system in fifteen Italian preschool children with SLI and found that the SLI children performed significantly worse than their MLU matched peers. Errors of omission were most common.

Various studies have investigated the production of articles in Spanish. Most of these studies found results similar to those found in other languages: children with SLI perform worse than their age-matched peers and errors of omission are by far the most common (Bedore & Leonard, 2001; Bosch & Serra, 1997).

There is one study on Spanish that reports substitution as the most common error. Restrepo & Gutiérrez-Clellen (2001) investigating patterns of article production in school aged children (age 5–7) found that substitutions due to errors in (morphological) gender assignment were the most common error produced by their group of SLI children. Overall correct performance rates, however, were quite high ranging from 77% to 83%.

To provide further insight into the error patterns in article production in Spanish SLI and specifically the role of gender, Anderson & Souto (2005) used an elicitation task as well as spontaneous speech samples to study article use in a group of 11 children with SLI (mean age 4 yrs; 10 months). The data consisted of three connected speech samples, as well as an experimental task. The purpose of the experimental task was to elicit a noun phrase consisting of an article as well as an adjective and noun. Importantly, in Spanish each noun has inherent gender (masculine or feminine) and both the article and the adjective have to conform to this gender (i.e. agreement). Adding an adjective to the NP in this experimental setup allowed the researchers to further investigate whether article gender errors are due to lack of knowledge of the noun's gender (which determines adjective morphology and selection of a gender specific article). If substitution errors in the article production were due to lack of grammatical knowledge about noun gender, one would expect the children to make similar errors with the adjectives. The task consisted of a modified barrier game in which the child was asked to describe the order of two pictures of similar objects on a picture card. As each object only differed from the other on one characteristic (e.g., colour) the child had to use an adjective to perform the task accurately. The results of the spontaneous speech analyses showed that the group of SLI children performed significantly worse than their age matched peers. In addition error analyses revealed that omission was the most frequent error (87.2%) followed by substitution of gender (9.5%). On the experimental task the age matched group showed higher accuracy levels (94.5%) than the SLI group (64.3%). Furthermore, errors in the SLI group were predominantly due to omission of the article (78.9%), with some gender substitutions (21.1%). The analysis of the adjective production in this task suggests that the article gender errors that the children make are neither due to inherent difficulties with gender, nor difficulties with agreement in general. In most cases, when the child produced the wrong gender for the article, the adjective *did* conform to the noun's grammatical gender. In addition each noun was elicited twice and variability was such that one noun was used with the correct article once and an error occurred in the second production. It thus seems that the difficulties that children with SLI experience with the production of articles is not due to lack of grammatical knowledge, but rather that there is a problem with the noun-article connection.

Hansson, Nettelbladt & Leonard (2003) investigated the production of definite and indefinite articles in Swedish children with SLI. This study provides further evidence that omission and substitution of articles in children with SLI is not due to lack of grammatical knowledge. As also discussed in the section on article production in aphasia in Swedish the indefinite article occurs as a free grammatical morpheme, whilst the definite article is marked by a suffix added to the noun. Both indefinite and definite articles furthermore have two phonological forms expressing gender. Definiteness can also be expressed using a free grammatical morpheme, but this only occurs when the noun phrase contains an adjective. In this case, the noun is preceded by a definite article in addition to the suffix. The authors used spontaneous speech as well as an elicitation task to investigate the role of prosody on error patterns in article production. They show that unstressed syllables occurring in a pre-stress position are more susceptible to omissions and errors than elements immediately following a stressed syllable. Based on this phonological account they therefore hypothesize that indefinite articles will be more problematic to children with SLI than the definite suffix. They tested 13 children with SLI (age range 4;03 – 5;07), and MLU-matched control group (age range 2;09 – 3;07) and an age-matched group. The age-matched control group performed significantly better than both the SLI and MLU group, whereas the latter two did not differ. Both children with SLI and MLU children used indefinite articles significantly less than definite articles. However, a probe task similar to that used in Anderson & Souto (2005) further showed that the children did not have difficulties with indefiniteness per se. On this task the children had to produce article + adjective + noun phrases. As mentioned, in these constructions both definite and indefiniteness are expressed by the use of a free grammatical morpheme. In this probe task, the children with SLI had difficulties with both types of morphemes. The enhanced performance on definiteness thus only appears when expressed as a suffix. This seems to provide strong evidence for a prosodic explanation of error patterns in article production. However, the results also showed that the SLI group omitted the indefinite neuter article *ett* more often than the neuter indefinite article *en*. This cannot be explained by a prosodic account as both are weak monosyllabic morphemes of vc (vowel-consonant) structure.

In summary, children with SLI have difficulties with the production of articles. The extent of the difficulties seems to be dependent on the language that the child is acquiring. The most common error across all languages is error of omission, although most studies also show some substitution errors. It is unlikely that these errors of substitution are due to lack of grammatical knowledge on the child's part. It has been shown that the children do have knowledge of the noun's gender even when they make gender errors in the article and performance is variable both within and across participants. Theories assuming that SLI is due to a lack of grammatical knowledge struggle explaining these findings. Furthermore, when compared to typically developing children, SLI children show the same profile across article paradigms. Although the SLI groups in these studies performed significantly worse than their age, and sometimes language-matched peers, their pattern of performance was very similar. These factors all seem to indicate that children with SLI do not suffer from a lack of grammatical knowledge, but rather that they are acquiring morphology in the same way as TD children but have a more limited capacity using their knowledge. Although a phonological account proposed by Leonard Bortolini (1998) seemed to be able to explain some of the results found in the study on Swedish children, it could not explain all findings. In addition to possible difficulties processing weak phonological information, there thus seems to be another factor contributing to the difficulties of these children to retrieve the (correct) article upon producing the noun.

6.3.4 Retrieving Articles

Activation and retrieval of articles depend on the properties of the noun. Discourse information, semantic information, grammatical information on gender and information on the phonological context that the article will have to be produced in, all play a role in the selection of the correct article. The article system in the lexicon will therefore receive input from different systems at varying times during processing. Alario & Caramazza (2002) suggest that determiners are represented by means of a language specific frame with slots for each type of information. These slots must be filled with feature information provided by the noun. For Dutch, it has been shown that article selection and retrieval (Janssen & Caramazza, 2003) depend on information on number, gender and definiteness. All slots have to be filled before the correct determiner can be selected, but activation of the determiners occurs as information in the different slots becomes available. Only when all slots are filled and information on gender, definiteness and number are simultaneously active, can the determiner be selected.

Based on the studies discussed so far, I will assume that the children with SLI and adults with aphasia have all the information from the noun and discourse context that is necessary to activate the correct article. However, we still find numerous omissions of articles. It appears therefore that the activation of the connections to the article system in these speakers is insufficient for the (correct) article to be consistently selected and produced. In short, language disordered children and adults seem to have reduced capacity to select and retrieve the correct article, even when all the required information for selection is there.

As in literature on aphasia, reduced processing capacity has been a much-used term in the SLI literature and also a much debated one. In the current chapter, I propose a model based on information theory that provides a possibility to measure the degree of complexity within the article system, in order to explain article omission patterns and reduced processing capacity in language disordered speakers.

6.3.5 Introduction to KL Divergence

As discussed in the introduction, Claude Shannon proposed that for each message sent across a (technical) channel, a complexity level (entropy H) can be calculated. He found that every channel has a certain capacity. If the amount of entropy of the message that is put into the channel exceeds the channel capacity, the message will get distorted and there will be errors in the output. The channel capacity is thus the amount of entropy a certain channel can cope with in one unit of time (Kostiç & Katz, 1987). The degree of distortion of the message provides an index of the channel "goodness".

In order to estimate the difference between two probability distributions (and in our case the probability distribution of channel input and output) several measures can be used. Differential entropy defines the mutual information between random variables. Mutual information is a measure of dependence between two variables. It can be calculated by means of the Kullback-Leibler divergence which is a measure that quantifies in bits how close a probability distribution $p = \{p_x\}$ is to a model (or candidate) distribution $q = \{q_x\}$ (Cover

& Thomas, 1991). The mutual information is the KL divergence between the joint probability and the product of the marginal probabilities and is defined as:

[1] $$m_{KL}(P\|Q) = \sum p(x)\log\frac{p(x)}{q(x)}$$

As I will show below, the difference between the input and output probability distribution of articles in SLI speech as measured by the Kullback-Leibler distance, gives a clear prediction of the omission rates.

For our purposes, I do not need to go into all of the technical details of channel capacity as described in information theory. What is important, however, is that the model is content-independent, that is, the *nature* of the message does not matter for measuring its degree of complexity and for determining the channel capacity. A message (in its technical sense) can be anything from a single letter to the entire War and Peace; it can be electrical signals sent across a wire, or information shared by DNA molecules. Or, relevant for us, it can be feature information "sent" by a selected noun (which is to be produced) to the set of articles. As I will argue below, it is precisely this process of "sending" the (available) feature information to the article that is under developed in SLI (and in younger typically developing children). Or, in terms of information theory, the channel capacity of the noun-article system in the population is lower than in typically developing children of the same age. Lower in such a way that it allows for making measurable predictions about the distribution and production of articles. Importantly[9], a reduction in channel capacity by itself is not necessarily problematic, or, in fact is problematic only if the information is transmitted at maximum rate. I do not think that this is *a priori* the case. What I do want to suggest is that the capacity in SLI is reduced to such an extent that it actually does result in distortion of information flow. At the end of this chapter

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[9] As an anonymous reviewer of the published version of this chapter pointed out.

I will also speculate why this might be the case and how I believe this is part of a developing language system.

6.3.6 Application of Information Theory to Language Acquisition

De Lange (2008) used an information theoretical approach to explain article omission patterns in Dutch, Italian and German typically developing pre-schoolers. She found that the information load (I) for individual articles played a role in the acquisition process of those articles. Articles with higher information loads were used later than those with low information load. In addition to looking at individual articles, she used a modified formula to calculate the entropy for the Dutch, German and Italian article sets. She found that the higher the entropy of these sets, the more articles the children omit and the later they acquire them. More specifically, she found that out of the three languages, the Dutch article set has the highest entropy value. Using longitudinal spontaneous speech data she also found that Dutch children omit articles until a later age than German and Italian children. She argues that young children have limited processing resources and that rather than there being a difference between the brain maturation of Dutch, German and Italian children, the level of complexity of the article systems in the respective language differs. A lower complexity of the article system means that less brain maturation is required to cope with the system. This leads to the finding that Italian children start producing articles at an earlier age than Dutch children.

Ferrer i Cancho & colleagues (2002, 2004, 2005a, 2005b, 2008) have used several measures based on information theory to investigate a range of linguistic phenomena. In Ferrer i Cancho et al. (2002) the authors use mutual information as a measure for the strength of correlation between two words. They argue that strong links between words are a priori harder to establish for high frequency words than lower frequency words. As I will argue below, for children with SLI this means that they do not have difficulties with articles and nouns per se, but with the strength of the links between them. The association between the article and the noun may be weaker than for example the association between noun and adjective (as the results showed in Anderson & Souto, 2005), simply because strong links are more difficult to establish with high frequency words.

Peperkamp et al. (2006) combined statistical measures from information theory in combination with linguistic constraints to describe the acquisition of allophonic rules in French. One phoneme typically has varying phonetic specifications depending on the context in which the phoneme is produced. Children have to learn which allophones are present in a given language for a given phoneme. Peperkamp et al. developed a statistical learning algorithm based on the notion that different allophones of one phoneme generally occur in different contexts. They used Kullback-Leibler divergence to measure discrepancies in context probabilities for each pair of phonemes. When combined with linguistic filters their algorithm was able to detect allophonic distributions in French.

The above studies show that the developing human brain is sensitive to complexity of linguistic information and that information with high complexity requires more processing load. Furthermore, the models used in information theory are able to predict and explain variations in processing load by providing individual words or sets of words with a quantitative measure of complexity.

Returning to the previously mentioned study, De Lange showed that omission patterns of articles in language of typically developing children can be explained as the result of limited processing resources, as shown by cross-linguistic variation. From the studies described above, I know that children with SLI show omission of articles up to a much later age than typically developing (TD) children. In the current chapter I propose that the article omission patterns, as well as the distribution patterns of produced articles, can be explained by a model based on information theory. In this model I combine the article selection model by Janssen & Caramazza (2003) and the information theory of Shannon (1949). As article selection depends on the information the article set receives from the activated noun, I represent the linguistic noun–article dependency as Shannon's information channel.

The main hypothesis is that children with SLI have a reduced processing capacity and that this leads to distortion in the channel that uses information from the noun to select the correct article. Furthermore, the aim is to find out whether the same mechanism is responsible for article omissions in Dutch aphasic speakers, in other words, if a developing language system and a damaged language system have a particular property (i.e. reduced processing capacity) in common. In order to test this hypothesis spontaneous speech samples for a group of Dutch SLI children and a group of Dutch adults with aphasia were analysed. Omission and substitution rates for all articles were noted and the role of article type investigated. Finally, an analysis of the data using and information theoretic approach will be presented.

6.4 Method and Materials

6.4.1. Participants

For the SLI group, speech data for 12 children was selected from the Bol & Kuiken (1990) database. In this database children were tested on non-verbal IQ, which fell within normal range for all these children, as reported by Bol & Kuiken. Mean Length of Utterance (MLU) and Verbal Utterances (VU) scores are also provided. MLU measures the mean number of morphemes in an utterance and the VU score is a measure of the proportion of utterances that contain verbs.

Age	Gender	MLU	VU
5;03 (4 ;01–6 ;01)	7 boys, 5 girls	3,5 (2, 2–4,4)	0,44 (0,23–0,6)

Table 2. Age, gender, mean length of utterance (MLU) and verbal utterance (VU) scores. Standard deviation (SD) is provided in brackets for MLU and VU.

For the aphasic group, 12 non-fluent speakers were selected. 10 came from a joint project with Zilverschoon (2009) and 2 samples were also used in the chapter on Zipf's law. Participant details are presented in table 3.

	Sex	Age	Occupation	Cause	TPO
AN	M	73	Chief administration	CVA	20
IH	F	57	Secretary	CVA	1.7
JW	M	41	Senior consultant	CVA	2.6
AK	M	82	School director	CVA	2
MK	F	63	Saleswoman	CVA	1.6
SH	F	34	Manager	CVA	0.5
RB	M	49	Service station attendant	CVA	0.5
ME	M	30	Road worker	CVA	0.2
Barn	M	40	Motor mechanic	CVA	?
Heck	M	44	Construction draftsman	aneurysm	?
JvdH	F	36	Daycare	Multi infarct	7
JJ	F	63	Taxi driver	CVA	6

Table 3. Participant information for the aphasic speakers. Time post onset in years.

6.4.2 Materials and Scoring

Speech samples for the children consisted of spontaneous speech during a free-play session with either a researcher or a speech therapist. For each child at least 100 utterances were used in the analysis. For the aphasic individuals speech data consisted of a semi-structured interview on their history of illness, family, job, and their hobbies. As the samples were often shorter than 100 utterances, full samples were used. The shortest sample was 30 utterances. Unintelligible utterances, direct repetitions of a researcher utterance, idiomatic expressions, rhymes and songs were excluded from the analyses. For each file the number of articles was calculated and type of article marked. In addition, all article omissions and substitutions were marked. All situations in which a noun was produced and an article would have been required in adult speech were counted as omission. Percentages of omission were calculated for each individual article as well as the overall omission rate. These calculations were then used to provide two types of measures:

The *distribution* of article use of the participant (*i.e.* the relative distribution of *de, het* and *een*—the three articles of the Dutch language) and of the required article set were calculated. Note that these measures do not deal with absolute numbers of what is produced or should have been produced. Rather, they provide a measure of the distribution between the three articles. Furthermore, sentence position of the article was noted as well as finiteness of the sentence the article should have been produced in.

6.5 Results

Statistical analyses using Mann-Whitney shows that for the SLI group there is no significant difference between the omission rates of *de* and *het*, *de* and *een* or *een* and *het.*

Mean % omission	**Mean % substitution**
36.5 (28)	2.8 (4.1)

Table 4. Error analyses: mean overall percentage and SD of omissions and substitutions.

Mean	***de***	***het***	***een***
36.5 (28)	32.6 (32.5)	53.6 (37)	41.8 (34.5)

Table 5. Percentage of omission and SD per article for children with SLI.

For the aphasic group Mann-Whitney analysis showed an effect of individual articles ($F(2,11)=3.812$, $p<.05$). Post hoc analyses revealed that only the difference between omission rates of *de* and *het* were significant ($F(1,18)=0.701$, $p<0.05$). There was no significant difference for the definite articles de and het and the indefinite article een. Only one subject used substitution, and only two times (*de* for *het*).

Mean	*de*	*het*	*een*
46.1 (28)	30 (32.1)	68.2 (37)	46.1 (27.9)

Table 6. Percentage of omission and SD per article for adults with aphasia.

6.5.1 Article Omission Patterns for *het* in Children with SLI

Het omissions were further scrutinised and the nouns divided into two groups: neuter nouns requiring *het* and diminutive nouns that always require *het* regardless of their base noun gender. In Dutch all diminutives require *het* regardless of their stem. For example *het boek* (the book) becomes *het boekje* (the book-DIM), but *de poes* (the cat) also becomes *het poesje* (the cat-DIM). Mann-Whitney shows that for the SLI group *het* was omitted significantly more often for diminutive nouns than neuter nouns (see figure 1, $z= -2.024$, $p< 0.05$). I come back to why this may be important in language processing terms in the discussion. For the aphasic group the diminutive was only used twice. No further analyses were performed for this group.

Within the group of diminutive nouns there was no difference between the omission rates of nouns with a common base and those with a neuter base (figure 2). DP represents nouns that are correctly produced with an article (determiner + noun), in NPs no article was produced.

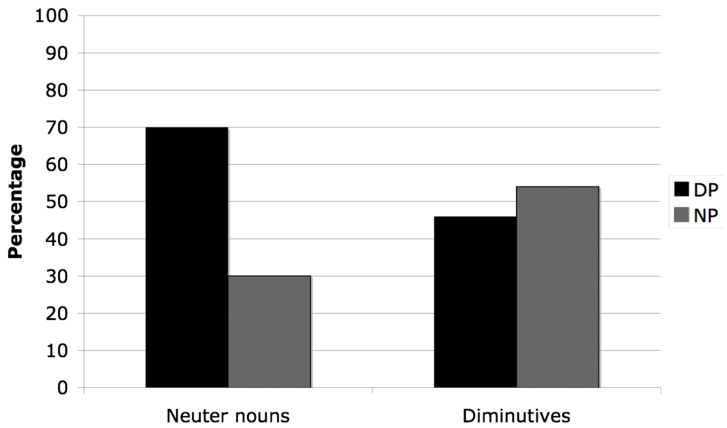

Figure 1. Group data of production of Determiner Phrases (DP) and Noun Phrases (NP) for neuter nouns and diminutives. *Het* is significantly more often omitted (NP) for diminutives than neuter nouns.

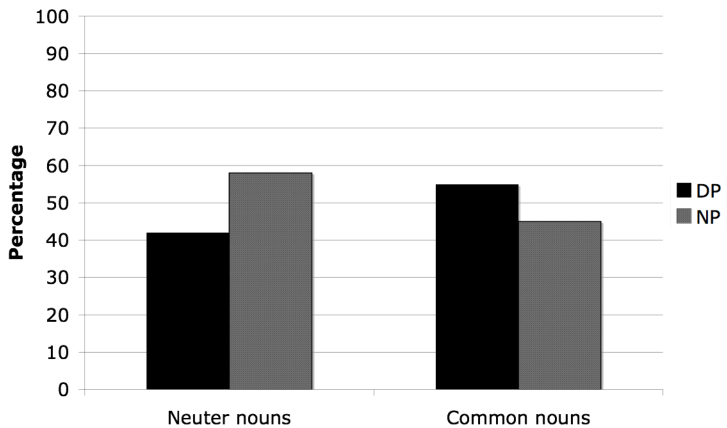

Figure 2. Group data of production of DP and NP for diminutives with a neuter base noun and a common base noun.

6.5.2 Information Theoretic Analysis

Only those files were used in which omission rate was below 50% for information theoretic analyses as suggested by De Lange (2008). This meant that for the group of SLI children four files were excluded. For the aphasic participants two files were excluded for this reason. In addition one of the aphasic participants made no errors of omission or substitution in his articles. This sample was therefore also excluded from further analyses.

First of all, the effect of *information load (I)* of the individual articles was investigated. This measure takes into account the number of functions one article can have, as well as its frequency. Frequency measures were taken from the Corpus Gesproken Nederlands (CGN), a collection of approximately nine million spoken Dutch words. The following number of functions was distinguished (as also discussed by de Lange, 2008):

de 1. sg/common/def.
2. pl/common/def.
3. pl/neuter/def.
4. dim/pl/common/def.
5. dim/pl/neuter/def.

het 1. sg/neuter/def.
2. dim/neuter/def.
3. dim/common/def.

een 1. sg/common/indef.
2. sg/neuter/indef.
3. pl/common/indef.
4. pl/neuter/indef.

The information load I was then calculated as below:

[2] $$I_e = -\log_2\left(\frac{F_e/R_e}{\sum_e F_e/R_e}\right)$$

where R_e denotes the number of functions and meanings carried by element e and F the frequency of a form.

	Frequency	Nr functions	I
De	253,210	5	1.33
Het	96,327	3	1.98
Een	179,119	4	1.51

Table 4. Frequency, number of functions and information load of individual articles.

It was then investigated if omission of a certain article can predict the overall omission rate, in other words, if omission rates are due to poor performance on one particular article. I already showed in Section 2.1 that information load of the individual items does not lead to a significant difference in number of omissions for children with SLI. For adults with aphasia however, there *is* a difference between the different articles. *Het* is by far the most often omitted, in fact four participants overall and two participants with average omission rates of below 50 percent omit *het* 100% if the time. Due to the small numbers it is impossible to analyse whether this is due to a frequency effect of the individual articles (*het* being far less frequent than the other two), or whether it can be better explained by the individual information load effect (*het* being the most information load heavy). It is clear however, that the pattern of errors for the SLI children and the aphasic adults is different in this respect. Figure 3 shows the regression lines of the correlation between overall omission rates and omissions of (a) *de*, (b) *het* and (c) *een* with R^2 and significance level (p). In the graphs on the left each dot represents one child. The dots on graphs on the graphs on the right represent one aphasic patient.

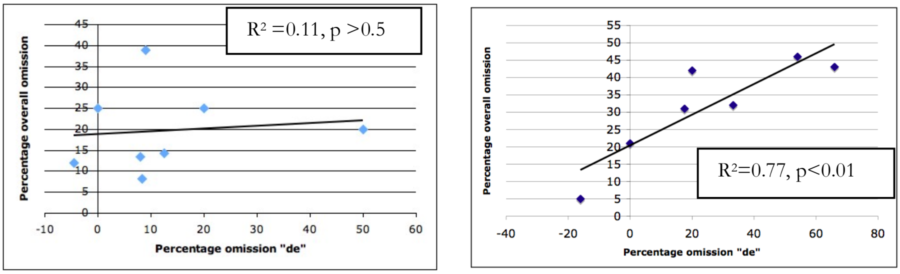

Figure 3a. Regression lines between overall omission rates and omissions of *de*

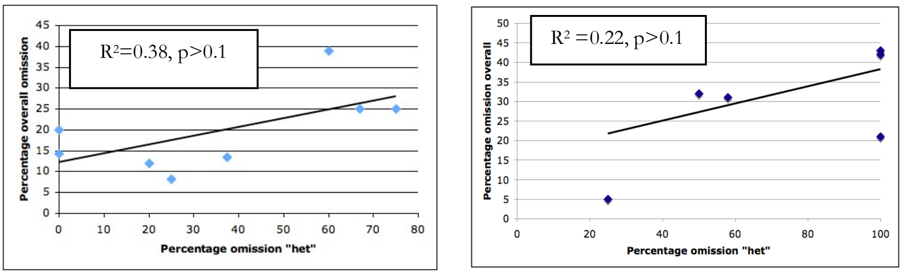

Figure 3b. Regression lines between overall omission rates and omissions of *het*

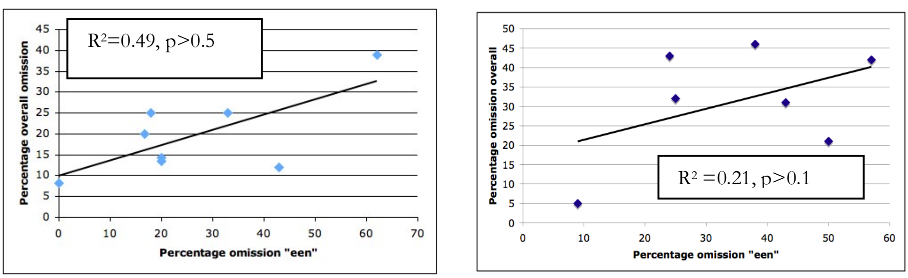

Figure 3c. Regression lines between overall omission rates and omissions of *een*

To make sure that for the children with SLI it was not the case that omission rates of one particular article are responsible for changes of overall omission rates, regression analysis was performed between individual omission rates of articles and overall omission rates. In other words, it could be that children with reduced processing capacity have more difficulties producing the article with the highest individual information load. Even though this does not show when comparing average omission rates of the individual articles, it could be that omission of one of the articles explains differences in overall omission rates. Figure 3 however shows that this is not the case. For the aphasic adults however, figure 3 clearly shows that omission rates of *de* correlate strongly with overall omission rates. This is unsurprising, as *de* is the only article that shows variation in omission patterns between patients. *Het* is very difficult for all but one patient.

To investigate whether the data can be described by representing the process of "noun-article" communication as Shannon's channel, the probability distribution of the articles was examined. This distribution was calculated on the basis of the nouns produced by the speaker (with or without an article).

I do acknowledge that the validity of this approach is based on the assumption that the speaker has acquired the necessary feature specification of the nouns he/she produces. In other words, the assumption is that if a child or patient produces what is in healthy adult speech a singular masculine noun, then it is indeed a singular masculine noun in the patient or child's system as well and that it is singular masculine feature that are to be transmitted to the article set. I believe this is a reasonable assumption given the age of the participants, previous claims in the literature (see above) and by the (virtual) absence of substitution errors in the data.

The Kullback-Leibler divergence was used to measure the distance between the probability distribution of the article set the child should have produced (q) and that of the article set the child actually produced (p). Thus as measure of the "input message" for the channel I used the distribution of the required articles in a file. For each noun the required article was marked. This provides a distribution of the articles required in a sample and represents the information sent from the noun set to the article set for one child. Now crucially for this method it is required that q and p are not zero. As 5 out of our remaining 9 aphasic patients omitted 1 article 100% of the time, this analysis was impossible for their sample. The other four patients were included.

To investigate whether this "message" from the noun is accurately transmitted to the article selection system, the probability distribution of the output was calculated. To this end, I used the probability distribution of the articles that the speaker actually produced. If the speakers produced all the required articles, the article distribution would be identical to the input.

The Kullback-Leibler divergence was then applied for each pair of probability distributions (i.e. for each speaker). This provided us with an index of how similar the article distribution the speaker uses is to the article distribution the child should have used in that particular conversation, if the feature information from the noun were correctly "transmitted" to the articles set. Table 5 displays probability distributions, KL divergence and overall percentage of omission for each speaker.

$$[1]\quad m_{KL}(P\|Q) = \sum p(x)\log\frac{p(x)}{q(x)}$$

Participant	Input (q)			Output (p)			KL div	% omit
1	0.62	0.15	0.23	0.8	0.08	0.12	0.112	39
2	0.13	0.12	0.75	0.08	0.15	0.8	0.02	20
3	0.52	0.29	0.19	0.62	0.24	0.14	0.03	13
4	0.42	0.11	0.47	0.44	0.04	0.52	0.053	25
5	0.43	0.18	0.39	0.58	0.08	0.33	0.526	25
6	0.08	0.33	0.58	0.09	0.27	0.64	0.897	8
7	0.57	0.07	0.36	0.58	0.08	0.33	0.003	14
8	0.66	0.21	0.13	0.72	0.16	0.12	0.015	13
AK	0.16	0.21	0.63	0.15	0.15	0.69	0.016	32
JJ	0.35	0.15	0.5	0.29	0.19	0.52	0.017	5
HECK	0.59	0.22	0.18	0.71	0.14	0.15	0.048	32
AN	0.39	0.14	0.46	0.33	0.13	0.53	0.014	47.5

Table 5. Article distribution of the input (q), output (p), KL divergence and percentage of omission for each child (1-8) and aphasic participant (AK, JJ, HECK and AN).

The hypothesis was that the underlying reason for article omission is the underdeveloped or reduced capacity of the channel responsible for transmitting the information from the selected noun to article set. Input to the channel is represented by (q) and output by (p). The closer the probability distribution of the input is to the output, the better the channel does its job by correctly transmitting information from the noun to the article set. In other words, it provides an index of the channel's capacity to transmit information. If the hypothesis is correct, there should be a correlation between percentage of omission and the KL divergence, as both measures are determined by the same factor: channel capacity. Figure 4 shows the regression line for this correlation for the children with SLI.

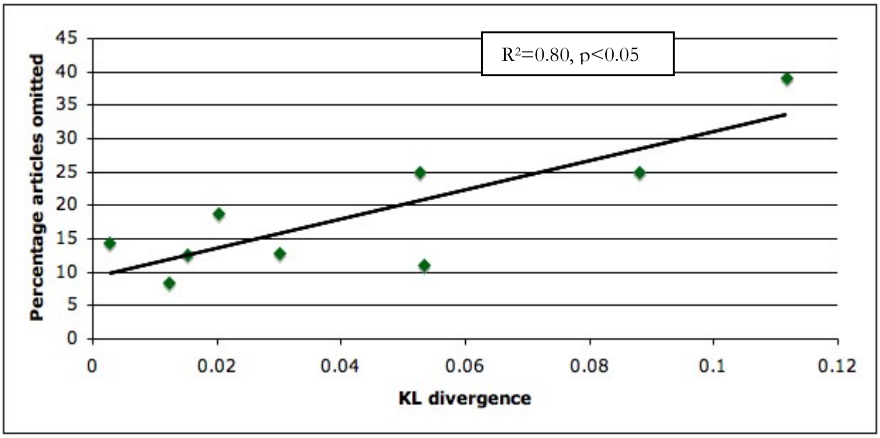

Figure 4. Correlation between KL divergence and overall percentage of article omission.

$R^2 = 0.80$ ($p < 0.05$) for the correlation between KL divergence and percentage of omission. There is thus a strong correlation between KL divergence and the percentage of omission of articles for each child.

For the adults with aphasia there was no correlation between KL divergence and overall omission rate.

6.6 Discussion

This study investigated the omission and substitution patterns of articles in spontaneous speech samples for a group of 12 Dutch children with SLI and a group of 12 non-fluent aphasic patients. I will now first discus our findings for the SLI group, followed by a discussion of the findings for the aphasic group and a comparison between the two.

6.6.1 SLI

The data show that errors of omission are by far the most common type of error these children made. Mean percentage of omission in our samples was 36 percent, whilst mean percentage of substitutions was only 2.4 percent. This finding is in line with most of the studies discussed in the introduction. Although Restrepo & Gutiérrez-Clellen (2001) found substitution to be the most common error to be made by their Spanish cohort of SLI children, the vast majority of studies report omission as the most common error, both in spontaneous speech and experimental tasks. The substitution errors the children did make in our Dutch samples were all *de* for *het* substitutions. This is a common finding in typical language acquisition in Dutch. Van der Velde (2004) for example found that in a production task comparing Dutch and French preschoolers, the Dutch children often substitute the common definite article *de* for the neuter definite article *het*. In contrast, the French preschoolers in that study did not show this pattern. Zonneveld (1992) argues that Dutch children use *de* as an unmarked, default article for nouns of which they know the meaning but are unsure of the gender.

This line of reasoning, however, seems unlikely for this group of SLI children. If *de* were used as a default article I would expect much higher substitution rates. Furthermore, comparing omission rates of the three articles I find that none of them is significantly more often omitted than the others.

Before I can conclude that the omission patterns are not due to lack of grammatical knowledge, one further phenomenon in Dutch language acquisition should be mentioned; the use of diminutives. In Dutch all diminutive nouns take *het* as their article, regardless of the gender of the base noun from which they are derived. Thus, the neuter base noun *het boek* (the book) becomes *het boekje* (the book-DIM), but the common base noun *de leeuw* (the lion) also becomes *het leeuwtje* (the lion-DIM). Schaerlaekens (1980) suggests that forming a diminutive is one of the earliest morphological skills of Dutch speaking children. Furthermore, diminutive nouns are frequent in child directed speech. Zonneveld (1992) further observed high accuracy rates in the production of *het* in young typically developing children when used with diminutive nouns. It could therefore be the case that the accuracy rates for *het* are skewed by a high usage of diminutives in our speech samples. In order to produce the correct article for a diminutive, the child does not need to use their knowledge of the gender of the noun. It could be that these children use a high number of diminutives and that they accurately produce the article for these. Neuter nouns could still have high omission rates, but this could be masked by high accuracy rates on diminutives. If this were the case, children's article production difficulties may still be the result of poor gender knowledge. In order to investigate this possibility, the data for nouns taking *het* were reanalysed and split into two groups: neuter nouns and diminutives. If gender provides a difficulty for these children I would expect higher accuracy rates on the diminutives than the neuter nouns. Error analysis of omission of *het* for our data reveals quite the opposite pattern (see figure 2 above). Children have more difficulties producing *het* when using a diminutive noun than when they use a nonderived neuter noun. Further inspection shows that they have equal difficulties with those nouns that are derived from common base nouns as those with neuter nouns. The children are not helped by the article of the base noun. They make equal number of errors with nouns such as "*het leeuwtje*" (the lion-DIM) derived from "*de leeuw*" (the lion) as with nouns such as "*het boekje*" (the book-DIM) derived from "*het boek*" (the book). It thus seems that, if anything, gender knowledge *is* present and is actually inhibiting selection of the correct article. The increased uncertainty of competing articles for the base noun and the diminutive form leads to decreased performance. This provides further support for our hypothesis that the difficulty in producing articles is related to the noun-article connection.

Interestingly, similar results have been found in adult language processing. Schiller & Caramazza (2003) found longer naming latencies for Dutch adults for diminutive nouns with a common gender base, compared to those with a neuter gender base. They argue that this is due to activation of the common article that goes with the base noun, upon production of the diminutive noun.

This leads to competition between the articles and therefore longer latencies. For diminutive nouns that have neuter base gender this competition does not occur, as the base noun will activate the same article as the diminutive form of that noun. The gender feature of the base noun thus seems to be activated in the article selection process. The error pattern of the Dutch SLI children is in line with these findings for adults. Dutch SLI children do have knowledge of the gender of the noun but, paradoxically; this knowledge can even lead to decreased performance. Competition between the articles leads to increased processing load and a failure in selecting any of the articles.

The effect of sentence position on omission patterns was also investigated. Contrary to some findings in the literature on typically developing children (Schoenenberg, Penner, & Weissenborn, 1997) for German and (Avrutin, 2004b) for Dutch, I did not find a sentence position effect.

As lack of grammatical knowledge does not appear to be the cause of omission of articles for these children, the data were analysed using an information theoretic approach. As discussed in the introduction, recent studies have shown that processing time can be accurately described using information-theoretic measures. First, the effect of the individual information load for each article was investigated using formula (1). This factor did not seem to determine patterns of omission in the children's output.

The difference between input and output probability distribution of the articles was then used to provide us with an index of the processing capacity of these children. Probability distributions were calculated for the articles that each child should have produced and for what the child actually produced. The first distribution represents the input of the channel: the information that is sent from the nouns to the article set. The second probability distribution represents the output of the channel. KL divergence was used to investigate the difference between these two probability distributions. I hypothesized that when the channel capacity is sufficient for these children, the output will have the same probability distribution as the input. The KL divergence was used as an index of the amount of distortion that occurs in the channel. In other words, the greater the divergence, the more different the output is from the input and the further the child's article distribution is removed from what it should be[10].

KL divergence was then correlated with overall percentage of omission. The correlation between these two variables was over 0.8. This means that the more different the article distribution of the child's production was from what it should have been, the more articles were *also* omitted. Again, it is crucial to realise that the KL divergence measure does not take omissions into account. Rather it provides a measure of how similar the output of a channel is to the input. If the channel capacity is sufficient, output and input will be identical. The difference between output and input provides a measure of the level of distortion that has occurred within the channel. As we observed that the rate of omission correlated with the KL divergence value, *and* as this value is an index of channel capacity to correctly transmit information, it follows that the omissions in SLI speech can be characterised as a consequence of low channel capacity.

This chapter has provided more evidence for a processing account of SLI. Unlike previous accounts, I have tried to develop a quantitative measure for the

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[10] It is crucial to note that neither the measure for input entropy nor the measure for output entropy use information on omissions. Input entropy provides a measure of what the article distribution should be like, *i.e.* the information the nouns sent to the article selection system in that sample, and the output entropy provides a measure of the article distribution the child actually produced. It is important to note that these, in theory, could be identical regardless of the number of omissions the child made. *I.e.* if the required input consisted of 100 nouns with the probability distribution of the articles of 0.2, 0.4, and 0.2 and the output consisted of 50 articles with the probability distribution of 0.2, 0.4 and 0.2, input and output entropy would have been identical even though 50% of articles was omitted.

reduced processing in children with SLI. Here I have focused on the production of articles and shown that a measure of channel capacity as described by information theoretical means can provide a model for the reduced processing capacity these children experience. Similar findings have been reported for a group of typically developing Dutch and Italian children (de Lange, 2008). De Lange looked at Dutch preschoolers with a very similar language level to the children with SLI reported on in this paper. Her results show that channel capacity increases with age and the number of omitted articles reduces. This is evidence for the view that children with SLI follow a similar developmental trajectory as typically developing children.

Although this chapter has only looked at article production, I can also tentatively speculate that reduced processing capacity may be involved in other aspects of language difficulties these children experience. Inflectional morphology has been shown to be difficult for these children (Bishop, 1992), (Leonard & Bortolini, 1998), with some inflections being more difficult than others. The previous chapters on inflectional morphology in Dutch (Tabak, Schreuder, & Baayen, 2005) has shown that different inflectional forms of verbs have different complexity in terms of information theoretical measures and that these influence speed of processing in healthy and aphasic adults. Future research will have to provide more insight into whether these factors play a role in the difficulties of children with SLI in producing inflectional morphemes.

Speed of processing has also been shown to be reduced in children with SLI (Fazio, 1998), (Montgomery, 2005). Children with SLI are slower on a wide range of (language) tasks, and reducing the input rate of language stimuli can improve performance on comprehension tasks for these children (Montgomery, 2005). As channel capacity is a measure of the amount of information the channel can process in *one unit of time*, it follows that in order to perform accurately one can either reduce the amount of information, or increase the amount of time to enhance performance. This is exactly what happens when the speed of input is reduced.

For typically developing children it has been shown that speed of processing increases with age (Marslen-Wilson & Tyler, 1981). Within our current model, this means that channel capacity increases with age. Montgomery (2005) showed that a similar development occurs for children with SLI, *i.e.* they show a linear improvement in speed of processing with an increase in age. However, the children's speed of processing remains below that of their age matched- and (in the Montgomery study) language matched peers. In other words, their channel capacity is reduced in comparison to TD children.

If processing capacity is reduced, the obvious next question is whether this reduction is apparent only for language tasks, or whether it is a more general reduction in the processing of information. Despite the requirement of normal non-verbal intelligence for a child to be diagnosed as having SLI, there is a growing amount of research suggesting that the difficulties of children with SLI may not be completely 'language specific'. For example, children with SLI have shown difficulties with spatial processing (Kamhi, Catts, Mauer, Apel, & Gentry, 1988), hierarchical planning tasks (Cromer, 1983; Kamhi et al., 1988) and hypothesis testing (Nelson & Apel, 1987; Ellis Weismer, 1991). Johnston (1999) provides an excellent overview of the literature on the cognitive abilities that have been investigated in SLI and shows that many non-verbal skills lag behind those of typically developing children. Some motor skills have also been shown to be problematic for this group of children (see Hill, 2001) for an overview). In short, it seems that the reduced processing capacity these children experience may not be language specific. Instead a more general difficulty processing complex information could lead to a more diffuse profile of difficulties in various cognitive domains. Although I can not draw any conclusions on nonverbal skills from our findings, it would be interesting to find out what the performance of children with SLI would be on a task similar to that reported for aphasic adults in chapter 4.

6.6.2 Aphasia

The results for the aphasic speakers show a different pattern to the children with SLI. Omission rates were very different for the different articles, with *het* being the most difficult for all speakers and four speakers omitted this article in 100% of the cases. *De* and *een* had very similar omission rates. Within the current design it is impossible to say whether this result shows a definiteness effect, or whether frequency of the article plays a role. Of course, it was not the goal of the current chapter to investigate the effect of definiteness, but our findings seem to be in line with those of Bastiaanse & Havik (2010), definiteness does not appear to play a role in retrieval; there appears to be no obvious difference between the definite articles *de* and *het* and the indefinite article *een*.

An information-theoretic approach to the omission rates was also explored for the aphasic adults. Individual information loads for the articles corresponded to omission patterns; the article with the highest information load (*het*) was omitted most often, followed by *een* and *de*. Although this is an interesting finding, the current sample size is too small to differentiate the effect of information from a mere frequency effect. Future research with a more structured setup providing larger numbers of articles could investigate this possibility.

The KL-divergence was calculated for those patients who produced all articles at least once. Unlike the child data, there was no correlation between the KL-divergence and percentage of omission. The aphasic omission patterns cannot be explained by a change in probability distribution of the article set.

6.6.3 General Discussion

The findings in this chapter show that article omissions in Dutch SLI children seem to be due to a reduced processing capacity. This makes it difficult for children to select the correct article corresponding to the noun produced. This can be captured by a model based on information theory that uses probability distributions to calculate channel capacity. I have shown that the level of distortion in the probability distribution from the nouns to the article set provides a measure of the reduction of channel capacity. The more deviant the output probability distribution from the input distribution, the higher the omission rates of articles in a spontaneous speech sample. Furthermore, similarity between older SLI children and younger typically developing (TD) children with regard to omission and distribution of articles suggests that SLI can be characterized, at least in part, as a disorder related to late maturation of the processing capacity which is necessary to realize the available knowledge.

In contrast, the omission patterns of the adults with aphasia could not be captured by this model. Instead, their omission patterns seemed to be more related to the difficulty retrieving individual articles. Articles with the low frequency rates, and high information loads were omitted more often than those with high frequency rates and low information load. It thus seems that the proposed model captures a process of development, rather than of language disorder. The maturing brain of both typically developing and SLI children is unable to process the complexity of the adult article set. For adults with aphasia on the other hand, the adult article set has already been engrained into their lexicon. Retrieving the correct individual article seems to be what causes omission patterns in this group of language impaired individuals.

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7 OVERALL DISCUSSION AND CONCLUSIONS

In this last chapter I aim to answer the main research questions posed in chapter one and to provide a general discussion on the use of information theoretic measures in language disorders.

7.1 Research questions

In chapter 1 the following main research questions for this project were posed:

1. To what extent can limitation of information processing capacity as measured within an information theoretic paradigm explain apparent agrammatic behaviour in Dutch people with aphasia?
2. Is the above limitation language - specific or it is observable in other cognitive domains, specifically visual cognition?
3. To what extent can limitation of information processing capacity as measured within an information theoretic paradigm explain the article retrieval difficulties of Dutch children with Specific Language Impairment?

7.2 Why information theory?

If the interested reader has managed to read all 6 previous chapters in detail, they should by now feel somewhat familiar with information theory and its main concepts. As discussed in the introduction, combining these mathematical, abstract concepts of probability, entropy and information load with linguistics in general and language disorders in particular may have initially felt somewhat far-fetched. The motivation for the search for a framework in which linguistic material could be quantified, came from the discontent I experienced with current linguistic and processing approaches to language disorders. Those that claim (grammatical) knowledge is lost or broken could not explain the language profiles of the aphasic patients I work with; under specific circumstances these patients *are* able to perform linguistic tasks that they otherwise find very hard. Intuitively it was therefore clear to me that processing of some form was the culprit in the language difficulties of most of these patients. But "processing" and "reduced processing capacity" are amongst the most underspecified concepts in the aphasia literature. What does it actually mean to have limited processing capacity and crucially, how do we measure this? Information theory provided some (but absolutely not all) answers to this problem. As I stated in the introduction, I do not claim information theory is the Holy Grail in aphasia research, nor does the use of these information theoretic tools imply that I think the mental lexicon is organized in terms of optimally coded bit streams. I have remained agnostic about how paradigmatic structure is implemented in the brain, as the type of experiments used in this project do not provide us with information on neural correlates. I do however believe information theory offers the right tools for studying the processing consequences of (paradigmatic) relations in the lexicon. And that it therefore could provide a small step towards a better understanding of what happens in the lexicon of language impaired individuals.

I will first discuss the findings from chapters 2, 3, 5 and 6 to answer research question 1, after which I will compare the results from the auditory lexical decision task (chapter 3) and the visual search task (chapter 4) to answer research question 2. I will then discuss the findings on children with SLI as reported in chapter 6 to answer question 3.

7.3 Research Questions and Answers

7.3.1 Research Question 1

To what extent can limitation of information processing capacity as measured within an information theoretic paradigm explain apparent agrammatic behaviour in Dutch people with aphasia?

The bulk of this thesis addresses this first research question. Both experiments (chapters 2 and 3) and spontaneous speech (chapters 5 and 6) were used to probe the use of information theory to answer this question. I did not set out to investigate all agrammatic aspects of aphasic speech. I focussed on aphasic speakers' difficulties with inflected verbs, articles and general word finding difficulties. In chapters 2 and 3 I described a lexical auditory decision experiment performed by 3 groups of speakers: healthy young and elderly and aphasic participants. This experiment used linguistic stimuli known to be particularly difficult for aphasic speakers: inflected verbs.

The results of chapter 2 showed that two information theoretic measures reliably affect response latencies of young and healthy elderly people. The first measure, information load, provides a complexity value of individual verb forms. It is based on the form frequency of the verb form and on the number of functions that specific verb form can fulfil. The second measure, inflectional entropy, captures the complexity of the probability distribution of the inflectional paradigm of the verb. The first measure had a negative effect on processing latencies: the higher the information load of an individual verb form, the longer the latencies in word recognition. The second measure had a positive effect on latencies (in word recognition). I suggested that this is because word forms in high entropy inflectional paradigms have short and strong connections. In psychological terms closeness in probability distribution was suggested to mean more equality among base levels of activation. In high entropy families activation of the family members boosts the activation level of the target, which means the target word is faster in reaching the threshold for word recognition.

In chapter 2 I showed that these factors affect latencies of healthy young and elderly participants to the same degree. Although minor differences in performance for the auditory lexical decision task did occur between the two groups, there was no interaction between any of the within-subject factors and group, indicating that the process of word recognition does not change significantly with age.

In chapter 3 I compared performance on the same auditory lexical decision task for aphasic participants and elderly control participants. The aphasic participants had no difficulties performing the lexical decision task; performance was well above chance. This finding indicates that the lexical representations are still present in the lexicon for the aphasic individuals, i.e. the lexicon has not degraded to the extent that lexical entries have gone missing. Furthermore the results showed that frequency and number of synsets affected latencies to the same degree for both groups. The number of synsets was added as an independent factor to investigate semantic connectivity in the lexicon. High semantic connectivity, as measured by a high number of synsets, leads to faster word recognition. The fact that the effect of semantic connectivity was in the same direction and of the same size for healthy elderly and aphasic participants was taken as evidence that the overall structure of the mental lexicon of aphasic participants had not changed after their CVA, the networks between words are intact.

The groups significantly differed in how their latencies were affected by the information theoretic measures. Participants with aphasia showed less benefit of a high entropy inflectional paradigm and, unlike the healthy participants, information load of individual verb forms had no effect on reaction times for aphasic participants. These two combined findings suggest that processing of bits of information does not occur in the same way for aphasic and healthy participants. Aphasic participants are less efficient than healthy adults at processing information as measured by these information theoretic measures. More specifically, I interpreted these findings to indicate that the ability to distinguish the target form between other forms within the inflectional paradigm is significantly harder for aphasic speakers.

Chapters 5 and 6 focussed on spontaneous speech data of aphasic speakers. I proposed two other uses of information theory: the relation between Zipf's law and entropy in chapter 5 and the use of the Kullback-Leibler divergence to investigate article retrieval in chapter 6. In chapter 5 speech from aphasic individuals from semi-structured interviews were analysed to investigate the balance between maximisation of information transfer (I) and cognitive effort, as measured by entropy (H). Ferrer i Cancho (cf. 2005) argues that Zipf's law (a power law that states that given a natural language sample, the frequency of any word is inversely proportional to its rank) is a fundamental result of this balance between information transfer and cognitive cost. He also argues that speakers with Zipf regression slopes that deviate from those found for healthy, intact adult language users, such as young children, might not be able to overcome the cost of communication as in normal adult speech, due to brain limitations. They (unknowingly) balance communication towards saving the cost as much as possible, in other words keeping H to a minimum.

Chapter 5 set out to investigate this possibility for our aphasic speakers. The results showed that the spontaneous speech data of aphasic speakers do adhere to Zipf's law. This is an interesting finding on its own, as their productive language can be argued to be fundamentally different to language samples produced by healthy speakers. I argued in the introduction of chapter 5 that Zipf's law follows as output of a complex system, in this case the lexicon. The current finding that aphasic speech conforms to Zipf's law therefore suggests that the basic organisation of the lexicon is the same for both groups. The difference between the samples of the healthy and aphasic speakers is the *slope* of Zipf's curve. For the aphasic samples the slope is reduced. In other words, although Zipf's law still holds, the balance between I (information transfer) and H (cost of communication) has shifted. This finding is in line with theories asigning aphasic word finding difficulties to lower processing rates rather than structural defects of the system. People with aphasia are unable to process the same level of H as adults with a healthy brain.

The results of these two parts of the thesis converge in the following way: linguistic representations are still present in the brain and the basic organisation of verbal paradigms and the lexicon as a whole seems unchanged. The results of chapter 6 on the other hand are somewhat different. This chapter set out to investigate omission of articles using a third information theoretic measure: the Kullback-Leibler divergence. This is a measure that quantifies in bits how close a probability distribution $p = \{p_x\}$ is to a model (or candidate) distribution $q = \{q_x\}$. I set out to investigate processing of the connection between articles and nouns by comparing the probability distribution of the articles the participants should have produced (q) to the probability distribution of the articles they actually produced (p). This KL measure was proposed to capture the capacity of the system that selects articles for corresponding nouns. The greater the KL measure, the more reduced I suggested the channel capacity of the article-noun connection system is. For young typically developing children this measure has been shown to correlate to overall omission rates of articles (de Lange, 2008), even though this does not a priori need to be the case. I found that, unlike the children with SLI, the approximated reduction in channel capacity did *not* predict the observed omission rates of articles for the aphasic speakers. Rather, it seems that rather than the complexity of the probability distribution between the three articles, it is the information load of individual article that plays na important role in ease of retrieval for people with aphasia.

The findings from these 4 chapters allow us to answer research question 1 in the following way: Yes, information theoretic measures can capture and describe some of the apparent agrammatic behaviour of aphasic individuals. Although there is still a long way to go, this thesis shows that using information theory to gauge complexity of verbal items as well as the lexicon as a whole is a fruitful exploration. It provides us with measures to quantify linguistic complexity and therefore allows for specific predictions about aphasic behaviour within a reduced processing framework. Of course the logical next question is whether this processing is reduced for linguistic material only, or whether we can see it in other cognitive domains, such as visual cognition. This leads us to research question number 2:

7.3.2 Research Question 2

Is the above limitation language - specific or it is observable in other cognitive domains, specifically visual cognition?

Creating an experiment that could answer this question proved to be the most challenging task of this thesis. Visual cognition is a huge research field and combining information theory with visual search was a struggle. The initial goal was to create a visual search task that could be directly compared to our lexical decision task. However, as information load did not predict the reaction times latencies for the aphasic individuals in the language task, it was impossible to directly correlate complexity and performance on the two tasks. I did however manage to use an information theoretic approach to the visual search data and use this to make specific predictions about the performance of the aphasic individuals. If processing of complex information, in particular uncertainty as measured by the difference between targets and distractors, is the culprit in both linguistic and non-linguistic tasks, we expected performance of the aphasic individuals to drop significantly more than for healthy controls on visual search displays with a low salient target. Saliency was calculated using Shannon's information theory, creating saliency maps for each visual display. Reaction times showed that performance of the participants with aphasia was not significantly poorer overall. Rather, when uncertainty was increased, by decreasing the saliency of the target, performance dropped significantly in comparison to the healthy controls.

In other words, when a target item needs to be found within a group of neighbours (be it other verb forms in the inflectional paradigm within the lexicon, or a small circle in a visual display of larger circles) people with aphasia struggle significantly more than healthy control participants when the uncertainty is high (i.e. when targets and distractors are more alike). The limitation in processing of information is not language specific and is observable in at least one other cognitive domain: that of visual cognition.

7.3.3 Research Question 3

To what extent can limitation of information processing capacity as measured within an information theoretic paradigm explain the article retrieval difficulties of Dutch children with Specific Language Impairment?

Although it was beyond the scope of this project to carry out all experiments and analyses for both aphasic adults and children with SLI, the final chapter does directly compare the two groups of language impaired invidivuals. The general stance is that, although both disorders have a different aetiology, they are both characterised by reduced processing abilities and it may be possible to model this in a parsimonuous way using information theoretic measures. The analyses used in chapter 6 further developed an approach suggested by De Lange (2008). Using a cross-linguistic approach, she found that for typically developing children age of acquistion of articles is correlated to the entropy of the set of articles for the acquired language. Children acquiring Italian, with an extensive article system but a low entropy within this system, begin to produce articles at an earlier age than Dutch children, who are acquiring a language with a simple article system but with high entropy. Furthermore, she found a developmental pattern comparing the speech output of individual children at different ages. There was a correlation between omission rates and the difference between the probability distribution that should have been produced (input), based on the produced nouns and the articles the children actually produced (output). As the probability distribution of the input became more similar to the output with age, the percentage of omissions reduced.

In chapter 6 I investigated if similar results for a group of older children with SLI, who typically have article production patterns similar to much younger typically developing children. I further developed the measure comparing input and output by using the Kullback-Leibler divergence between the two probability distributions. I found that in line with De Lange's findings, there is a correlation between the KL divergence (which reflects an approximation of the channel capacity of the system) and the percentage of omissions. This is *not* what we found for the aphasic adults also discussed in that chapter.

It therefore seems that this finding captures reduced processing in the developing brain and therefore a maturation process, rather than a limitation due to a language disorder. The crucial difference between the lexicons of aphasic speakers and children with SLI is that the former is a system in which (at least function words) have been long acquired and have formed stable representations. The probability distribution of the three articles in their lexicon most likely closely mirrors the probability distribution of the three articles that de Lange (2008) calculated from the Corpus Gesproken Nederlands. The probabalistic characteristics of the lexical representations of articles in the lexicon of children (whether language-impaired or not) is still developing. The suggested channel capacity measure (KL divergence) therefore seems to capture how closely matched the child's probabalistic representations of the article system in his/her lexicon is to that what it eventually should be once language acquisition is complete. The interesting question therefore is whether developmental pattern of the children with SLI mirrors that of the younger typically developing children described by De Lange, and whether eventually channel input will equal output and the percentage of omission reduces to zero. If older children with SLI *still* show difficulties with article production, I would expect performance to be more similar to the performance of the aphasic adults described in this thesis. Complexity of individual articles would influence ease of retrieval.

The answer to question 3 therefore is, that we can capture reduced processing of article production in SLI using an information theoretic measure. Furthermore, this finding indicates that the article production difficulties children with SLI have are due to maturation difficulties, similar to younger typically developing children. I cannot make any further compelling claims about similarities between SLI and aphasia. Before we can do this, we would have to use a similar approach suggested in chapters 2 and 3 for a group of children with SLI.

7.4 Some Final Thoughts and Clinical Implications

7.4.1 Other Verb Forms in the Paradigm

One of the differences between chapters 2 and 3 was that chapter 2 reported on past tense stimuli as well as infinitive verb forms. For practical reasons it was decided only to use one set of verb forms for the aphasic participants and the past tense list was the obvious choice as we assumed, based on the literature, that this verb form was most likely to show differences between the aphasic and healthy speakers. It would however be of interest to perform the experiment on aphasic participants using the infinitive verb forms as well as the inflected past tense forms. For most (but not all) verb paradigms, the infinitive form is also the one with the lowest information load. It could be that this is the reason that speakers with aphasia often find it easier to use this form, rather than the 3rd person singular or other inflected form. One could speculate that it is the information load combined with the inflectional entropy of the paradigm that determines which forms are difficult for the aphasic participants.

7.4.2 Productive Language and Information Theory

Originally I set out to investigate production of verb forms as well as recognition. It would be extremely interesting to find out if speakers with aphasia show effects of the information theoretic measures on the speed and accuracy of the production of verb forms. Tabak et al. (2005) used a picture naming task of the same verbs used in the lexical decision experiments reported here and found that for young healthy speakers information theoretic measures do predict response latencies. For aphasic individuals, especially those with non-fluent aphasia, it would be rather challenging to create an experiment that only taps into their ability to process information. Many more factors affect production, which is why for the purpose of this thesis I decided to only use a simple recognition task and spontaneous speech data.

7.4.3 Individual Data

For the auditory lexical decision task the participants' individual data did not have sufficient power to provide significant results. For the visual task the individual data mirror the group data presented in chapter 4 for all participants. The lack of statistical significance on the auditory data meant it was impossible to directly compare performance on the auditory and visual tasks for individual cases. Of course I could have looked at the overall performance in terms of number of errors or reaction times (i.e. was the patient with lowest RTs on the auditory task also the fastest on the visual task), but we feel there is not much point in performing this analysis. The core of this thesis revolves around within-subject performance, in particular the effects of an increase of complexity of the stimuli materials. Simply showing that fast participants have short latencies on both tasks would not add any useful information to my findings.

7.4.4 Clinical Implications

As pointed out in the introduction this research project was mainly theoretically motivated. The main purpose was to gain a better understanding of the structure of language in general and of the underlying processes responsible for aphasic language in particular. Of course, as a speech and language therapist, for me the ultimate goal of all research on aphasia is to improve our understanding, diagnosis and treatment of people with aphasia. I would therefore like to spend a few paragraphs on the clinical implications of this research project. First of all, I should emphasise that although the conclusions of chapter 3 indicated that the semantic structure of the lexicon of the aphasic participants in this study seemed intact, this does *not* mean that the semantic system is intact for *all* aphasic patients. As all SLTs (should) know, there is a large group of patients for whom word-finding difficulties have a semantic origin. These patients usually also have (severe) language comprehension difficulties. The findings of this thesis therefore do not apply to this group of patients.

For patients whose semantic network does appear largely intact, the findings of this thesis do have clinical implications. The facilitatory effect of number of synsets on latencies in the auditory lexical decision task for the aphasic participants reflects intact connectivity between lexical items in the lexicon. This finding suggests that cueing as part of aphasia therapy could boost the neuronal circuit the target word form is part of and therefore enhances ease of retrieval. Furthermore, the results in chapters 2 and 3 showed that the strength of a memory trace in long-term memory is not just determined by how often one hears/uses the verb form, but how often on average a verb form is used in a specific grammatical context. I therefore suggest that intensive therapy using verb forms in realistic linguistic settings could strengthen memory traces and therefore increase saliency and positively affect ease of retrieval.

A second clinical implication comes from the finding that these results support the view that all verb forms are stored as complete units in paradigmatic families in the lexicon. These paradigmatic connections could influence access and ease of retrieval. In language production tasks, producing verb forms from high inflectional families (i.e. with densely connected inflectional paradigmatic structure) is more difficult than those with low inflectional families and could therefore hamper performance language production tasks. On the other hand, according to the complexity account of treatment efficacy (CATE) by Thompson et al. (2003) a complexity effect could be turned into an advantage in therapy. According to CATE treating more complex items in therapy has a knock-on effect on the more easy items of a given category. Future research will have to confirm whether verb therapy using highly complex verbs (based on these information theoretic measures) generalizes to verbs with a lower complexity.

A final finding that has clinical implications is the performance of the aphasic individuals on the non-verbal task. Although all the aphasic participants in this study seemed cognitively unimpaired (based on reports by their speech therapist and performance on the two cognitive tasks), the results on the visual task show that if complexity is systematically manipulated, these patients *do* show difficulties with non-verbal tasks. These findings further support the view that processing of all types of cognitive information may be impaired to some degree in patients with aphasia. This could influence both diagnostics and aphasia therapy.

7.5 Conclusions

In summary, this thesis provided a first attempt to investigate reduced processing in language-impaired individuals within an information theoretic framework. The results on an auditory lexical decision task, a visual search task and two types of spontaneous speech analyses for language disordered individuals and healthy controls showed that a) information theory provides us with the tools to quantify linguistic material and that b) we can relate the effect of this complexity to the (reduced) processing capacity in adults with aphasia and children with SLI. Although information theory does not provide all the answers, this thesis brings us one step closer to unraveling the mystery of (impaired) linguistic processing.

7.6 References

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APPENDICES

Appendix A. Verbs and pseudo verbs used in Chapters 2 and 3

	Infinitives		Pseudo inf		Past Sing
c1	hebben	d1	zebben	1	bleek
c2	worden	d2	worgen	2	gloeide
c3	zullen	d3	zilmen	3	glom
c4	kunnen	d4	kungen	4	rees
c5	gaan	d5	paan	5	wierp
c6	komen	d6	kulen	6	dolf
c7	zeggen	d7	feggen	7	snikte
c8	moeten	d8	moeden	8	liet
c9	zien	d9	zuin	9	sneed
c10	maken	d10	megen	10	schrok
c11	staan	d11	spoen	11	zette
c12	willen	d12	millen	12	blies
c13	doen	d13	wimmen	13	speelde
c14	laten	d14	doon	14	sprak
c15	weten	d15	leten	15	reeg
c16	denken	d16	waten	16	krabde
c17	geven	d17	dangen	17	bond
c18	blijven	d18	keven	18	werd
c19	vinden	d19	blaven	19	scheidde
c20	kijken	d20	vanken	20	smeet
c21	houden	d21	kupen	21	voegde
c22	krijgen	d22	hieden	22	doemde
c23	zitten	d23	kremen	23	mat
c24	nemen	d24	zidden	24	snoerde
c25	liggen	d25	nelen	25	schikte
c26	brengen	d26	miggen	26	stonk
c27	lopen	d27	branken	27	snapte
c28	vragen	d28	mapen	28	zeurde
c29	horen	d29	vrenen	29	vleidde
c30	mogen	d30	goren	30	zag

c31	voelen	d31	noken	31	klonk
c32	stellen	d32	ziemen	32	vlocht
c33	leven	d33	spollen	33	dook
c34	vallen	d34	meven	34	leerde
c35	spreken	d35	zellen	35	goot
c36	volgen	d36	straken	36	week
c37	kennen	d37	zalgen	37	streefde
c38	trekken	d38	gennen	38	strekte
c39	blijken	d39	treggen	39	zoog
c40	noemen	d40	drijken	40	scheurde
c41	leggen	d41	nuimen	41	rijmde
c42	schrijven	d42	naggen	42	bood
c43	halen	d43	sprijven	43	ploos
c44	zetten	d44	galen	44	had
c45	spelen	d45	zesten	45	vluchtte
c46	roepen	d46	spemen	46	gooide
c47	wachten	d47	doepen	47	loog
c48	leren	d48	zechten	48	zei
c49	praten	d49	loren	49	stoorde
c50	zoeken	d50	draten	50	snoot
c51	slaan	d51	zuiken	51	stichtte
c52	lezen	d52	slein	52	kocht
c53	lachen	d53	nuzen	53	trad
c54	dragen	d54	nalgen	54	vocht
c55	helpen	d55	blagen	55	trachtte
c56	hangen	d56	galpen	56	mikte
c57	dienen	d57	hongen	57	zakte
c58	leiden	d58	dunen	58	wrong
c59	steken	d59	leiven	59	woonde
c60	wijzen	d60	speken	60	brandde
c61	hoeven	d61	wozen	61	ging
c62	draaien	d62	hiezen	62	zwierde
c63	schijnen	d63	blaaien	63	wist
c64	raken	d64	stijnen	64	smeekte
c65	merken	d65	ralen	65	beefde

c66	wonen	d66	morken	66	sleurde
c67	slapen	d67	ronen	67	leed
c68	rijden	d68	slaten	68	zeilde
c69	sluiten	d69	rijven	69	bleef
c70	richten	d70	slouven	70	drong
c71	eten	d71	lechten	71	dronk
c72	klinken	d72	emen	72	deelde
c73	heten	d73	krangen	73	liep
c74	bieden	d74	geken	74	gromde
c75	zorgen	d75	buiden	75	hieuw
c76	kiezen	d76	vorgen	76	kneep
c77	lijden	d77	guizen	77	stikte
c78	pakken	d78	lijgen	78	steeg
c79	voeren	d79	panken	79	velde
c80	knikken	d80	zoeren	80	schaamde
c81	kopen	d81	knekken	81	greep
c82	menen	d82	keden	82	wees
c83	drinken	d83	mulen	83	zwom
c84	schieten	d84	drikken	84	wijdde
c85	drukken	d85	schieken	85	zwaaide
c86	sterven	d86	brukken	86	spoog
c87	tonen	d87	stessen	87	maakte
c88	hopen	d88	ponen	88	kostte
c89	durven	d89	gopen	89	sloot
c90	schudden	d90	darven	90	voelde
c91	zwijgen	d91	schunnen	91	sleet
c92	dringen	d92	zwogen	92	stortte
c93	springen	d93	brangen	93	dwong
c94	werpen	d94	splinken	94	lachte
c95	treden	d95	warden	95	droeg
c96	breken	d96	trepen	96	kookte
c97	stoppen	d97	droken	97	scheette
c98	gooien	d98	stummen	98	toonde
c99	schreeuwen	d99	booien	99	keek
c100	huilen	d100	sprieuwen	100	stoof

c101	trachten	d101	hijlen	101	hees
c102	schuiven	d102	trochten	102	spande
c103	kloppen	d103	sluiven	103	sprintte
c104	bellen	d104	kroffen	104	bracht
c105	sturen	d105	zelken	105	breide
c106	zingen	d106	spuren	106	sprong
c107	vliegen	d107	bingen	107	schoot
c108	grijpen	d108	vriechen	108	trilde
c109	staren	d109	glijmen	109	hield
c110	missen	d110	stulen	110	schold
c111	wensen	d111	bissen	111	beet
c112	trouwen	d112	jensen	112	bad
c113	bouwen	d113	prouwen	113	klaagde
c114	voegen	d114	beeuwen	114	viel
c115	treffen	d115	zoegen	115	redde
c116	schenken	d116	tressen	116	kromp
c117	rennen	d117	schemmen	117	droop
c118	schrikken	d118	lennen	118	droomde
c119	kosten	d119	schriffen	119	stootte
c120	dwingen	d120	gosten	120	stopte
c121	vangen	d121	dwiffen	121	wende
c122	winnen	d122	vengen	122	wendde
c123	drijven	d123	jonnen	123	snoof
c124	scheppen	d124	drijlen	124	zoende
c125	stijgen	d125	schummen	125	hief
c126	duwen	d126	spijgen	126	schudde
c127	vullen	d127	buwen	127	trof
c128	buigen	d128	gullen	128	meed
c129	delen	d129	kuigen	129	heerste
c130	glijden	d130	belen	130	slachtte
c131	wekken	d131	slijden	131	vond
c132	redden	d132	jenken	132	sliep
c133	letten	d133	medden	133	piste
c134	dreigen	d134	resten	134	spoot
c135	zakken	d135	bragen	135	pakte

c136	kruipen	d136	rakken	136	bouwde
c137	dromen	d137	kluiden	137	zweeg
c138	branden	d138	krenen	138	schiep
c139	snijden	d139	brinten	139	hoopte
c140	vechten	d140	sneten	140	kleedde
c141	wenden	d141	lochten	141	smolt
c142	varen	d142	genden	142	voedde
c143	wagen	d143	zaren	143	deed
c144	heersen	d144	lutten	144	kroop
c145	koken	d145	waarsen	145	daalde
c146	spijten	d146	lolen	146	lag
c147	zuchten	d147	spaten	147	gaf
c148	kussen	d148	vichten	148	leefde
c149	zwaaien	d149	kuffen	149	las
c150	dalen	d150	klaaien	150	drukte
c151	wennen	d151	nalen	151	dreigde
c152	heffen	d152	wessen	152	knikte
c153	vrezen	d153	hesten	153	schreef
c154	trillen	d154	glezen	154	schoof
c155	eisen	d155	prillen	155	holde
c156	kleden	d156	eiven	156	vulde
c157	danken	d157	speden	157	eiste
c158	jagen	d158	hanken	158	kon
c159	spannen	d159	tagen	159	vrat
c160	streven	d160	spaggen	160	schetste
c161	klimmen	d161	sproven	161	raakte
c162	slikken	d162	kremmen	162	reed
c163	leunen	d163	trikken	163	dankte
c164	scheiden	d164	luinen	164	voerde
c165	stemmen	d165	schoden	165	sloop
c166	schikken	d166	spommen	166	lette
c167	wrijven	d167	schinnen	167	slikte
c168	binden	d168	wraven	168	blonk
c169	strelen	d169	dinten	169	droogde
c170	strekken	d170	strolen	170	schreeuwde

c171	duiken	d171	strenken	171	huilde
c172	vatten	d172	muiken	172	dacht
c173	storten	d173	vammen	173	zat
c174	vluchten	d174	stirten	174	klom
c175	bijten	d175	vrichten	175	schaafde
c176	stoten	d176	dijgen	176	rende
c177	bidden	d177	spieten	177	koos
c178	vegen	d178	ditten	178	spoelde
c179	zenden	d179	vogen	179	merkte
c180	blazen	d180	venden	180	won
c181	stelen	d181	krazen	181	mocht
c182	barsten	d182	spalen	182	vroor
c183	rijzen	d183	dirsten	183	hikte
c184	meten	d184	luiven	184	zoop
c185	zwemmen	d185	mechen	185	trouwde
c186	liegen	d186	klebben	186	scheelde
c187	klagen	d187	diegen	187	richtte
c188	gillen	d188	krogen	188	staakte
c189	wijden	d189	hillen	189	boog
c190	knijpen	d190	wijmen	190	draaide
c191	scheuren	d191	knijten	191	wekte
c192	drogen	d192	schopen	192	stierf
c193	voeden	d193	blogen	193	vatte
c194	schatten	d194	zoeden	194	waadde
c195	smeken	d195	schempen	195	nam
c196	stichten	d196	sleken	196	streek
c197	storen	d197	steggen	197	vroeg
c198	beven	d198	stapen	198	wuifde
c199	stralen	d199	deven	199	scheen
c200	slepen	d200	stragen	200	wreef
c201	strijken	d201	stepen	201	hoorde
c202	wegen	d202	sprieken	202	zwierf
c203	zuigen	d203	welen	203	stemde
c204	vloeien	d204	vuigen	204	woog
c205	spotten	d205	slaaien	205	leunde

c206	schamen	d206	spoggen	206	noemde
c207	zweven	d207	spamen	207	legde
c208	schuilen	d208	zwenen	208	zou
c209	snappen	d209	schuipen	209	gleed
c210	glimmen	d210	snubben	210	dreef
c211	brullen	d211	gremmen	211	zong
c212	schelen	d212	drullen	212	school
c213	fluiten	d213	scheken	213	hielp
c214	grommen	d214	fluigen	214	klopte
c215	vergen	d215	glesten	215	trok
c216	schetsen	d216	zerven	216	veegde
c217	stinken	d217	schasten	217	zonk
c218	hollen	d218	stingen	218	prijsde
c219	wuiven	d219	gollen	219	schreed
c220	gloeien	d220	wuizen	220	stuurde
c221	prijzen	d221	kloeien	221	ving
c222	gieten	d222	prazen	222	spleet
c223	smijten	d223	hieten	223	praatte
c224	sluipen	d224	slamen	224	wou
c225	wijken	d225	sluiden	225	wachtte
c226	strijden	d226	wijgen	226	stond
c227	snikken	d227	strijten	227	zweefde
c228	snuiven	d228	snelken	228	zuchtte
c229	smelten	d229	spuiven	229	schatte
c230	zinken	d230	spedden	230	schoor
c231	spuiten	d231	zikken	231	vloeide
c232	zoenen	d232	spuilen	232	sleep
c233	zweren	d233	voenen	233	leidde
c234	scheren	d234	zwuren	234	brulde
c235	doemen	d235	sleren	235	kreeg
c236	breien	d236	doeben	236	riep
c237	druipen	d237	sleien	237	wierf
c238	krabben	d238	bruimen	238	straalde
c239	zwerven	d239	draben	239	kwam
c240	wringen	d240	zwargen	240	kuste

c241	spoelen	d241	wranken	241	groef
c242	blinken	d242	spoeven	242	duwde
c243	schelden	d243	blimmen	243	splitste
c244	graven	d244	schedden	244	durfde
c245	zweten	d245	klaven	245	vreesde
c246	vellen	d246	zwamen	246	staarde
c247	stikken	d247	vedden	247	streelde
c248	hijsen	d248	spikken	248	streed
c249	zeuren	d249	gijsen	249	sloeg
c250	krimpen	d250	veuren	250	diende
c251	vreten	d251	krippen	251	brak
c252	sleuren	d252	dreten	252	moest
c253	vriezen	d253	slouren	253	wreekte
c254	delven	d254	vrieden	254	vergde
c255	spugen	d255	belven	255	haalde
c256	wreken	d256	spulen	256	belde
c257	splitsen	d257	wruigen	257	porde
c258	zeilen	d258	splissen	258	zond
c259	stuiven	d259	vulen	259	stelde
c260	mikken	d260	sluinen	260	vloog
c261	vleien	d261	kruffen	261	sleepte
c262	vlechten	d262	pleien	262	voer
c263	slijten	d263	slichten	263	hing
c264	mijden	d264	plijden	264	wenste
c265	rijmen	d265	gijden	265	meende
c266	splijten	d266	rabben	266	zocht
c267	zuipen	d267	sprijten	267	schroefde
c268	slachten	d268	veupen	268	heette
c269	slijpen	d269	plochten	269	waagde
c270	schroeven	d270	klepen	270	hoefde
c271	schrijden	d271	sproezen	271	floot
c272	porren	d272	schrijmen	272	speet
c273	pissen	d273	sorren	273	kende
c274	snoeren	d274	piffen	274	barstte
c275	snuiten	d275	snoegen	275	zweerde

c276	waden	d276	snuipen	276	at
c277	werven	d277	zaffen	277	sproot
c278	rijgen	d278	werzen	278	spotte
c279	zwieren	d279	zwieven	279	zweette
c280	schaven	d280	schazen	280	gilde
c281	schijten	d281	snijten	281	zorgde
c282	hikken	d282	gikken	282	schonk
c283	houwen	d283	sprinken	283	miste
c284	sprinten	d284	spruinen	284	volgde
c285	spruiten	d285	drazen	285	stal
c286	pluizen	d286	plossen	286	joeg

	Pres Sing		**Pseudo Past Sg**		**Pseudo Pres Sg**
f1	heb	g1	zebde	h1	zeb
f2	word	g2	worgde	h2	worg
f3	zal	g3	zilmde	h3	zilm
f4	kan	g4	kungde	h4	kung
f5	ga	g5	pon	h5	paan
f6	kom	g6	kuulde	h6	kuul
f7	zeg	g7	feid	h7	feg
f8	moet	g8	moed	h8	moed
f9	zie	g9	zaap	h9	zuin
f10	maak	g10	meegde	h10	meeg
f11	sta	g11	spoonde	h11	spoen
f12	wil	g12	moud	h12	mil
f13	doe	g13	diede	h13	wim
f14	laat	g14	leet	h14	doon
f15	weet	g15	wasde	h15	leet
f16	denk	g16	dechte	h16	waat
f17	geef	g17	keefde	h17	dang
f18	blijf	g18	blaafde	h18	keef
f19	vind	g19	vankte	h19	blaaf
f20	kijk	g20	kuupte	h20	vank
f21	houd	g21	hied	h21	kuup

f22	krijg	g22	kreemde	h22	hied
f23	zit	g23	zalp	h23	kreem
f24	neem	g24	naal	h24	zid
f25	lig	g25	migde	h25	neel
f26	breng	g26	brankte	h26	mig
f27	loop	g27	maapte	h27	brank
f28	vraag	g28	vroen	h28	maap
f29	hoor	g29	goorde	h29	vreen
f30	mag	g30	nochte	h30	goor
f31	voel	g31	ziemde	h31	nook
f32	stel	g32	spolde	h32	ziem
f33	leef	g33	meefde	h33	spol
f34	val	g34	zielde	h34	meef
f35	spreek	g35	straakte	h35	zel
f36	volg	g36	zalgde	h36	straak
f37	ken	g37	gende	h37	zalg
f38	trek	g38	tregte	h38	gen
f39	blijk	g39	dreek	h39	treg
f40	noem	g40	nuimde	h40	drijk
f41	leg	g41	nagde	h41	nuim
f42	schrijf	g42	spreef	h42	nag
f43	haal	g43	gaalde	h43	sprijf
f44	zet	g44	zeste	h44	gaal
f45	speel	g45	speemde	h45	zest
f46	roep	g46	doepte	h46	speem
f47	wacht	g47	zechte	h47	doep
f48	leer	g48	loorde	h48	zecht
f49	praat	g49	draatte	h49	loor
f50	zoek	g50	zuikte	h50	draat
f51	sla	g51	sleig	h51	zuik
f52	lees	g52	naas	h52	slein
f53	lach	g53	nalgde	h53	nuus
f54	draag	g54	blaagde	h54	nalg
f55	help	g55	galpte	h55	blaag
f56	hang	g56	hong	h56	galp

f57	dien	g57	duunde	h57	hong
f58	leid	g58	leifde	h58	duun
f59	steek	g59	speekte	h59	leif
f60	wijs	g60	woos	h60	speek
f61	hoef	g61	hiesde	h61	woos
f62	draai	g62	blaaide	h62	hies
f63	schijn	g63	stoon	h63	blaai
f64	raak	g64	raalte	h64	stijn
f65	merk	g65	morkte	h65	raal
f66	woon	g66	roonde	h66	mork
f67	slaap	g67	sliet	h67	roon
f68	rijd	g68	reefde	h68	slaat
f69	sluit	g69	sleette	h69	rijf
f70	richt	g70	lechtte	h70	slouf
f71	eet	g71	aad	h71	lecht
f72	klink	g72	krong	h72	eem
f73	heet	g73	geette	h73	krang
f74	bied	g74	buidde	h74	geek
f75	zorg	g75	vorgde	h75	buid
f76	kies	g76	goos	h76	vorg
f77	lijd	g77	leette	h77	guis
f78	pak	g78	pante	h78	lijg
f79	voer	g79	zoerde	h79	pank
f80	knik	g80	knekte	h80	zoer
f81	koop	g81	kechte	h81	knek
f82	meen	g82	muulde	h82	keed
f83	drink	g83	drok	h83	muul
f84	schiet	g84	schook	h84	drik
f85	druk	g85	brukte	h85	schiek
f86	sterf	g86	stief	h86	bruk
f87	toon	g87	poonde	h87	stes
f88	hoop	g88	goopte	h88	poon
f89	durf	g89	darfde	h89	goop
f90	schudde	g90	schun	h90	darf
f91	zwijg	g91	zwaag	h91	schun

f92	dring	g92	brong	h92	zwoog
f93	spring	g93	splonk	h93	brang
f94	werp	g94	wiende	h94	splink
f95	treed	g95	traap	h95	ward
f96	breek	g96	drook	h96	treep
f97	stop	g97	stumte	h97	drook
f98	gooi	g98	booide	h98	stum
f99	schreeuw	g99	sprieuwde	h99	booi
f100	huil	g100	hijlde	h100	sprieuw
f101	tracht	g101	trochtte	h101	hijl
f102	schuif	g102	sleef	h102	trocht
f103	klop	g103	krofte	h103	sluif
f104	bel	g104	zil	h104	krof
f105	stuur	g105	spuurde	h105	zelk
f106	zing	g106	bong	h106	spuur
f107	vlieg	g107	vroog	h107	bing
f108	grijp	g108	gleem	h108	vriech
f109	staar	g109	stuulde	h109	glijm
f110	mis	g110	biste	h110	stuul
f111	wens	g111	jenste	h111	bis
f112	trouw	g112	prouwde	h112	jens
f113	bouw	g113	beeuwde	h113	prouw
f114	voeg	g114	zoegde	h114	beeuw
f115	tref	g115	treste	h115	zoeg
f116	schenk	g116	schom	h116	tres
f117	ren	g117	lende	h117	schem
f118	schrik	g118	schrof	h118	len
f119	kost	g119	gostte	h119	schrif
f120	dwing	g120	dwof	h120	gost
f121	vang	g121	vong	h121	dwif
f122	win	g122	jonde	h122	veng
f123	drijf	g123	dreel	h123	jon
f124	schep	g124	schemde	h124	drijl
f125	stijg	g125	speeg	h125	schum
f126	duw	g126	buwde	h126	spijg

f127	vul	g127	goolde	h127	buw
f128	buig	g128	koog	h128	gul
f129	deel	g129	boolde	h129	kuig
f130	glijd	g130	slied	h130	beel
f131	wek	g131	jekte	h131	slijd
f132	red	g132	medde	h132	jenk
f133	let	g133	ret	h133	medde
f134	dreig	g134	breigde	h134	rest
f135	zak	g135	rakte	h135	braag
f136	kruip	g136	klode	h136	rak
f137	droom	g137	kreende	h137	kluid
f138	brand	g138	brindde	h138	kreen
f139	snij	g139	sneeg	h139	brint
f140	vecht	g140	lochtte	h140	sneet
f141	wend	g141	gendde	h141	locht
f142	vaar	g142	zoer	h142	gend
f143	waag	g143	lutte	h143	zaar
f144	heers	g144	waarsde	h144	lut
f145	kook	g145	loolde	h145	waars
f146	spijt	g146	spiet	h146	lool
f147	zucht	g147	vichtte	h147	spaat
f148	kus	g148	kufte	h148	vicht
f149	zwaai	g149	klaaide	h149	kuf
f150	daal	g150	waalde	h150	klaai
f151	wen	g151	weft	h151	naal
f152	hef	g152	heste	h152	wes
f153	vrees	g153	gleesde	h153	hest
f154	tril	g154	prilde	h154	glees
f155	eis	g155	eifde	h155	pril
f156	kleed	g156	speedde	h156	eif
f157	dank	g157	hankte	h157	speed
f158	jaag	g158	toeg	h158	hank
f159	span	g159	spagte	h159	taag
f160	streef	g160	sproofde	h160	spag
f161	klim	g161	krim	h161	sproof

f162	slik	g162	trikte	h162	krem
f163	leun	g163	luinde	h163	trik
f164	scheid	g164	schoodde	h164	luin
f165	stem	g165	spomde	h165	schood
f166	schik	g166	schinte	h166	spom
f167	wrijf	g167	wraaf	h167	schin
f168	bind	g168	dont	h168	wraaf
f169	streel	g169	stroolde	h169	dint
f170	strek	g170	strenkte	h170	strool
f171	duik	g171	mook	h171	strenk
f172	vat	g172	vadde	h172	muik
f173	stort	g173	stirtte	h173	vam
f174	vlucht	g174	vrichtte	h174	stirt
f175	bijt	g175	beel	h175	vricht
f176	stoot	g176	spiette	h176	dijg
f177	bid	g177	daat	h177	spiet
f178	veeg	g178	voochte	h178	dit
f179	zend	g179	vont	h179	voog
f180	blaas	g180	kries	h180	vend
f181	steel	g181	spaal	h181	kraas
f182	barst	g182	dirstte	h182	spaal
f183	rijs	g183	leep	h183	dirst
f184	meet	g184	mechte	h184	luif
f185	zwem	g185	klobbe	h185	mech
f186	lieg	g186	noog	h186	kleb
f187	klaag	g187	kroogde	h187	dieg
f188	gil	g188	hilde	h188	kroog
f189	wijd	g189	wijmde	h189	hil
f190	knijp	g190	kneet	h190	wijm
f191	scheur	g191	schoopte	h191	knijt
f192	droog	g192	bloogde	h192	schoop
f193	voed	g193	zoedde	h193	bloog
f194	schat	g194	schempte	h194	zoed
f195	smeek	g195	sleekte	h195	schemp
f196	sticht	g196	stegte	h196	sleek

f197	stoor	g197	staapte	h197	steg
f198	beef	g198	deefde	h198	staap
f199	straal	g199	straagte	h199	deef
f200	sleep	g200	steepte	h200	straag
f201	strijk	g201	spriek	h201	steep
f202	weeg	g202	wool	h202	spriek
f203	zuig	g203	voog	h203	weel
f204	vloei	g204	slaaide	h204	vuig
f205	spot	g205	spogte	h205	slaai
f206	schaam	g206	spaamde	h206	spog
f207	zweef	g207	zweende	h207	spaam
f208	schuil	g208	schoop	h208	zween
f209	snap	g209	snupde	h209	schuip
f210	glim	g210	kron	h210	snub
f211	brul	g211	drulde	h211	grem
f212	scheel	g212	scheekte	h212	drul
f213	fluit	g213	floog	h213	scheek
f214	grom	g214	glest	h214	fluig
f215	verg	g215	zerfde	h215	glest
f216	schets	g216	schatste	h216	zerf
f217	stink	g217	stong	h217	schast
f218	hol	g218	gol	h218	sting
f219	wuif	g219	wuisde	h219	gol
f220	gloei	g220	kloeide	h220	wuis
f221	prijs	g221	praas	h221	kloei
f222	giet	g222	hoot	h222	praas
f223	smijt	g223	sleem	h223	hiet
f224	sluip	g224	sloot	h224	slaam
f225	wijk	g225	wijg	h225	sluid
f226	strijd	g226	street	h226	wijg
f227	snik	g227	snekte	h227	strijt
f228	snuif	g228	spoof	h228	snelk
f229	smelt	g229	spodde	h229	spuif
f230	zink	g230	zok	h230	sped
f231	spuit	g231	spool	h231	zik

f232	zoen	g232	voende	h232	spuil
f233	zweer	g233	zwoorde	h233	voen
f234	scheer	g234	soor	h234	zwuur
f235	doem	g235	doebde	h235	sleer
f236	brei	g236	sleide	h236	doeb
f237	druip	g237	broom	h237	slei
f238	krab	g238	drabde	h238	bruim
f239	zwerf	g239	zwierg	h239	draab
f240	wring	g240	wronk	h240	zwarg
f241	spoel	g241	spoefde	h241	wrank
f242	blink	g242	blomde	h242	spoef
f243	scheld	g243	schodde	h243	blim
f244	graaf	g244	kloef	h244	sched
f245	zweet	g245	zwaadde	h245	klaaf
f246	vel	g246	vedde	h246	zwaam
f247	stik	g247	spikte	h247	ved
f248	hijs	g248	gees	h248	spik
f249	zeur	g249	veurde	h249	gijs
f250	krimp	g250	kripte	h250	veur
f251	vreet	g251	draat	h251	krip
f252	sleur	g252	sloorde	h252	dreet
f253	vries	g253	vrood	h253	slour
f254	delf	g254	belfde	h254	vried
f255	spuug	g255	spuulde	h255	belf
f256	wreek	g256	wruigte	h256	spuul
f257	splits	g257	spliste	h257	wruig
f258	zeil	g258	vuulde	h258	splis
f259	stuif	g259	sloon	h259	vuul
f260	mik	g260	krufte	h260	sluin
f261	vlei	g261	pleide	h261	kruf
f262	vlecht	g262	slochte	h262	plei
f263	slijt	g263	pleed	h263	slicht
f264	mijd	g264	geed	h264	plijd
f265	rijm	g265	reeb	h265	gijd
f266	splijt	g266	spreet	h266	rab

f267	zuip	g267	voop	h267	sprijt
f268	slacht	g268	plochtte	h268	veup
f269	slijp	g269	kleep	h269	plocht
f270	schroef	g270	sproesde	h270	kleep
f271	schrijd	g271	schreem	h271	sproes
f272	por	g272	sorde	h272	schrijm
f273	pis	g273	pifte	h273	sor
f274	snoer	g274	snoegte	h274	pif
f275	snuit	g275	snoop	h275	snoeg
f276	waad	g276	zaafte	h276	snuip
f277	werf	g277	wiers	h277	zaf
f278	rijg	g278	zwoof	h278	wers
f279	zwier	g279	schaasde	h279	zwief
f280	schaaf	g280	sneet	h280	schaas
f281	schijt	g281	gikte	h281	snijt
f282	hik	g282	spronk	h282	gik
f283	houw	g283	sproon	h283	sprink
f284	sprint	g284	draas	h284	spruin
f285	spruit	g285	plos	h285	draas
f286	pluis	g286	wom	h286	plos

Appendix B. Past tense words lists with inflectional entropy (H) and information load (I)

Verb form	**I**	**H**	**LemFreq**	**FormFreq**	**nSynsets**
bleek	5.476	1.91	19597	718	1
gloeide	1.56	2.24	1000	10	3
glom	1.251	1.96	1124	2	2
rees	3.026	1.84	1592	4	4
wierp	1.501	2.1	4882	70	3
dolf	3.475	1.74	479	6	2
snikte	2.019	2.11	827	155	1
liet	2.091	2.04	66787	20700	12
sneed	2.871	1.89	2682	46	10
schrok	2.554	2.1	3622	1441	3
zette	2.125	1.87	17652	3099	4
blies	1.902	2.35	1737	253	4
speelde	2.818	2.25	16115	310	11
sprak	2.468	2.21	25142	784	6
reeg	7.474	0.58	136	2	3
krabde	1.79	2.37	704	100	1
bond	3.341	1.27	1979	54	10
werd	2.249	2.2	321883	2582	2
scheidde	4.874	1.04	2039	10	7
smeet	1.761	1.82	947	112	1
voegde	1.489	2.32	3866	470	5
doemde	3.741	1.48	715	60	1
mat	2.654	2.11	1585	413	3
snoerde	4.091	1.95	174	175	1
schikte	5.385	0.63	2024	121	5
stonk	1.761	2.05	1064	34	1
snapte	3.35	2.03	1125	524	3
zeurde	2.971	2.36	589	84	1
vleidde	3.112	1.42	320	71	1
zag	2.48	2.35	98375	15162	7
klonk	1.158	1.94	8091	126	5
vlocht	4.558	1.32	320	8	2
dook	1.608	2.45	1955	158	4
leerde	4.127	2.13	14686	2337	2
goot	2.163	1.97	980	256	4
week	1.073	1.69	14024	609	3

streefde	4.627	1.84	2147	46	1
strekte	2.437	2.28	1956	22	4
zoog	1.943	2.35	1312	46	5
scheurde	2.369	2.2	1476	157	7
rijmde	4.152	1.92	256	124	4
bood	2.961	2.13	7689	102	4
ploos	3.579	1.6	55	73	2
had	2.029	2.13	474965	56502	5
vluchtte	4.079	1.59	1836	2215	2
gooide	1.962	2.24	4594	246	1
loog	2.895	2.28	1554	98	2
zei	1.163	2.09	134802	8383	3
stoorde	3.907	1.58	1391	76	2
snoot	2.326	1.54	173	229	2
stichtte	4.551	1.02	1412	78	2
kocht	3.46	2.14	6942	1330	1
trad	2.672	2.19	4873	48	3
vocht	1.724	2.05	2651	252	4
trachtte	2.271	2.15	4477	1008	1
mikte	1.944	2.32	323	14	3
zakte	3.271	1.98	2849	2804	6
wrong	1.414	2.21	669	16	3
woonde	2.228	2.49	9026	563	1
brandde	4.598	2.2	2769	1695	6
ging	2.155	1.98	137589	11438	15
zwierde	2.854	1.97	128	106	2
wist	1.957	1.98	66735	32948	4
smeekte	1.35	2.29	1420	108	1
beefde	1.469	2.25	1381	60	2
sleurde	2.606	2.27	548	179	1
leed	4.711	1.31	7188	82	3
zeilde	3.286	2.05	417	312	2
bleef	2.004	2.4	52837	2294	5
drong	1.595	2.27	5164	42	3
dronk	2.744	2.44	6784	712	2
deelde	5.081	1.2	3233	13634	5
liep	1.557	2.43	35539	4716	9
gromde	0.632	1.67	1086	13	2
hieuw	5.514	1.34	92	34	2
kneep	1.083	2.15	1479	72	1

stikte	2.857	2.41	610	110	4
steeg	1.771	2.23	3335	22	3
velde	3.773	2.11	626	899	2
schaamde	1.701	2.3	1216	250	1
greep	1.044	2.03	4155	148	2
wees	2.176	2.48	10582	1332	5
zwom	2.656	2.09	1567	32	1
wijdde	-1	1.06	1485	1125	3
zwaaide	1.306	2.34	2347	216	3
spoog	2.277	2.43	436	106	3
maakte	2.982	2.16	86305	3227	4
kostte	2.909	1.95	3566	1703	2
sloot	2.749	1.58	8351	1184	8
voelde	1.314	2.28	29234	3418	7
sleet	2.704	2.11	310	52	5
stortte	2.071	2.09	1846	279	7
dwong	3.667	1.35	3451	48	2
lachte	1.611	2.39	12773	1672	1
droeg	1.941	2.34	11963	310	6
kookte	4.122	1.99	2436	344	4
scheette	1.839	2.17	119	87	1
toonde	3.177	2.2	5565	3639	5
keek	1.173	2.21	51564	5407	2
stoof	1.372	2.01	403	6	2
hees	1.182	1.99	594	19	2
spande	4.483	0.89	2165	93	4
sprintte	2.383	1.77	90	84	1
bracht	2.858	2.06	36536	1130	6
breide	4.047	2.12	705	25	1
sprong	1.297	2.29	5030	190	5
schoot	1.599	2.2	6642	1220	5
trilde	1.623	2.12	2278	17	3
hield	2.486	2.26	46508	2386	16
schold	1.938	2.31	659	24	1
beet	1.416	2.05	1829	317	3
bad	3.256	2.21	1782	118	4
klaagde	2.389	2.31	1544	34	2
viel	2.684	2.1	26001	1582	16
redde	4.685	1.53	3076	90	2
kromp	1.92	2.33	573	52	2

droop	0.975	1.97	705	4	1
droomde	3.925	1.87	2786	3542	3
stootte	1.803	2.16	1784	566	10
stopte	2.029	2.37	4691	645	8
wende	7.111	0.98	2297	22	3
wendde	2.72	1.31	2613	54	3
snoof	0.711	1.92	826	49	3
zoende	2.408	2.21	768	394	1
hief	1.491		2283	38	2
schudde	0.603	1.55	5241	100	2
trof	3.229	1.76	3840	67	5
meed	3.253	1.95	272	10	1
heerste	1.446	1.95	2511	20	3
slachtte	7.358	0.38	229	53	1
vond	2.419	2.43	51631	6314	3
sliep	3.218	2.18	8739	4126	5
piste	2.637	2.28	176	66	2
spoot	2.109	2.15	779	250	9
pakte	1.822	2.28	7159	2182	12
bouwde	5.035	1.67	3971	887	2
zweeg	1.627	2.33	5191	228	2
schiep	3.089	1.91	3344	149	4
hoopte	3.364	1.61	5399	6258	3
kleedde	3.806	1.49	2227	553	3
smolt	3.439	1.72	816	76	4
voedde	4.705	1.54	1466	18	6
deed	2.734	2.31	71277	6508	9
kroop	1.677	2.38	2836	104	5
daalde	2.295	2.37	2332	66	3
lag	1.79	1.95	40957	496	8
gaf	2.641	2.24	54472	3716	7
leefde	4.326	1.33	26762	498	4
las	2.738	1.96	12834	1168	5
drukte	2.417	2.05	6555	5733	8
dreigde	1.73	2.15	2903	20	2
knikte	0.502	1.48	6986	241	4
schreef	2.601	2.04	17958	952	6
schoof	1.491	2.21	4401	205	4
holde	2.599	2.03	1045	822	1
vulde	2.76	1.92	3245	110	2

eiste	3.56	2.25	2271	1054	2
kon	2.025	1.78	209812	92996	4
vrat	3.056	2.1	555	152	5
schetste	4.589	1.98	1066	371	2
raakte	1.791	2.34	9419	600	6
reed	2.485	2.18	8591	254	4
dankte	5.949	1.52	2222	3906	3
voerde	3.279	2.29	7087	838	8
sloop	2.963	2.41	925	30	1
lette	3.288	1.72	3053	976	3
slikte	2.063	2.24	2086	112	2
blonk	1.441	2.15	667	3	1
droogde	4.677	1.55	1469	1917	2
schreeuwde	1.224	2.29	4585	439	6
huilde	2.152	2.26	4580	190	2
dacht	1.86	2.37	58538	10626	6
zat	1.699	2.2	45810	11996	9
klom	1.78	2.45	2095	136	2
schaafde	3.089	2.04	120	9	6
rende	1.128	2.19	3707	115	1
koos	3.866	1.74	7555	403	3
spoelde	2.034	2.39	668	114	4
merkte	1.93	2.4	9381	1441	2
won	3.634	1.74	3383	68	6
mocht	2.009	1.73	30131	14444	3
vroor	2.839	1.87	482	250	2
hikte	2.227	1.74	116	80	1
zoop	3.028	2.26	237	18	2
trouwde	4.86	1.7	4006	1963	3
scheelde	3.358	1.89	1115	108	3
richtte	2.796	1.65	8289	1168	7
staakte	-1	2.39	10772	1556	11
boog	1.689	1.81	3234	104	5
draaide	1.133	2.2	9850	630	11
wekte	3.089	1.93	3171	22	2
stierf	2.853	1.98	6524	150	3
vatte	2.794	1.88	1854	845	3
waadde	4.176	0.9	171	4	1
nam	2.177	2.51	43709	4072	8
streek	0.79	1.77	4712	34	8

vroeg	1.614	2.22	34058	16452	8
wuifde	0.936	2.06	1030	32	2
scheen	1.589	2.01	9770	1088	2
wreef	1.156	2.14	2022	90	4
hoorde	2.345	2.38	33173	6043	7
zwierf	2.087	2.41	692	12	2
stemde	5.196	1.02	2028	11239	4
woog	3.252	1.96	1328	68	3
leunde	1.045	1.84	2083	32	2
noemde	3.746	1.82	18351	1168	2
legde	1.958	2.24	18068	969	5
zou	0.937	1.78	221958	56944	2
gleed	1.227	1.95	3193	18	1
dreef	2.301	1.96	3360	36	7
zong	2.385	2.35	4234	74	3
school	0.438	1.23	11295	334	2
hielp	3.199	2.18	11749	583	5
klopte	1.978	2.22	4350	148	6
trok	1.638	2.39	20145	1953	15
veegde	1.196	2.21	1760	130	3
zonk	2.239	2.3	786	72	1
prijsde	-1	1.48	63	3230	2
schreed	1.874	1.85	221	2	1
stuurde	3.26	2.08	4284	1307	5
ving	4.011	1.36	3435	70	5
spleet	2.006	1.7	768	28	2
praatte	3.47	1.92	14570	2102	3
wou	2.394	1.97	76697	33510	3
wachtte	2.256	2.06	14839	3466	3
stond	1.904	2.12	79616	1986	13
zweefde	1.553	2.27	1205	34	2
zuchtte	0.957	1.48	2420	1317	3
schatte	3.376	1.74	1430	1186	2
schoor	4.464	1.61	718	38	4
vloeide	2.349	2.07	1308	6	2
sleep	3.848	1.59	229	6	4
leidde	2.879	2.07	10955	88	6
brulde	0.789	1.89	1116	20	4
kreeg	2.276	2.4	45929	2624	3
riep	1.316	2.21	15111	897	4

wierf	4.53	1.91	167	99	2
straalde	2.128	2.22	1375	412	4
kwam	2.169	2.45	135035	9907	12
kuste	2.509	2.26	2365	724	1
groef	4.31	2.12	653	744	1
duwde	1.296	2.24	3288	234	3
splitste	4.118	1.85	427	10	3
durfde	1.771	2.37	5336	850	1
vreesde	3.103	1.99	2279	1847	3
staarde	1.376	1.96	4113	103	1
streelde	1.17	2.19	1961	78	2
streed	7.171	0.73	845	5103	3
sloeg	1.761	2.27	13752	760	10
diende	3.398	2.12	11429	953	7
brak	2.876	1.89	4762	108	9
moest	2.061	1.74	123371	63564	5
wreekte	4.117	1.91	431	8	3
vergde	3.486	1.91	1068	6	1
haalde	1.86	2.3	17748	1211	3
belde	2.346	2.24	4292	1371	4
porde	2.338	2.39	180	89	2
zond	2.583	1.85	1752	40	1
stelde	3.203	2.14	27078	3516	7
vloog	2.22	2.54	4232	444	6
sleepte	2.25	2.32	1371	85	3
voer	3.239	2.13	2550	39	3
hing	1.757	2.26	11746	296	8
wenste	3.155	2.35	4017	1748	2
meende	1.761	2.39	6839	1060	4
zocht	2.759	2.44	13945	2734	4
schroefde	2.536	2.22	226	105	1
heette	1.998	1.78	7793	4552	1
waagde	3.634	1.7	2533	111	2
hoefde	2.495	1.92	10197	1257	2
floot	1.923	2.05	1097	305	5
speet	3.542	0.6	2433	2650	1
kende	2.527	2.45	21514	2872	4
barstte	1.938	2.15	1602	551	3
zweerde	7.747	1.73	91	379	5
at	4.351	1.76	8283	1160	1

sproot	3.112	2.06	82	51	2
spotte	2.639	1.43	1249	503	4
zweette	3.98	1.01	644	1585	2
gilde	1.541	2.36	1540	238	3
zorgde	4.05	2.16	7608	3513	2
schonk	1.991	2.08	3745	182	3
miste	3.788	2.25	4093	1894	4
volgde	2.814	2.21	21720	308	7
stal	2.998	2.03	1621	261	1
joeg	2.808	1.59	2168	66	5

Appendix C. Infinitive words lists with inflectional entropy (H) and information load (I)

Verbform	I	H	LemFreq	FormFreq	nSynsets
hebben	3.348	2.13	474965	167226	5
worden	1.988	2.2	321883	75854	2
zullen	3.824	1.78	221958	113633	2
kunnen	1.936	1.78	209812	52291	4
gaan	2.142	1.98	137589	35093	15
komen	2.533	2.45	135035	37530	12
zeggen	3.173	2.09	134802	84742	3
moeten	2.171	1.74	123371	31941	5
zien	2.434	2.35	98375	25570	7
maken	2.034	2.16	86305	14511	4
staan	2.529	2.12	79616	27336	13
willen	2.878	1.97	76697	3488	3
doen	1.999	2.31	71277	18836	9
laten	1.568	2.04	66787	16405	12
weten	2.443	1.98	66735	19986	4
denken	2.464	2.37	58538	19358	6
geven	2.488	2.24	54472	13473	7
blijven	2.208	2.4	52837	15174	5
vinden	2.556	2.43	51631	12712	3
kijken	2.551	2.21	51564	24581	2
houden	2.546	2.26	46508	13090	16
krijgen	2.312	2.4	45929	11913	3
zitten	1.937	2.2	45810	17470	9
nemen	2.155	2.51	43709	12092	8
liggen	2.419	1.95	40957	12366	8
brengen	2.239	2.06	36536	7061	6
lopen	2.698	2.43	35539	15186	9
vragen	3.14	2.22	34058	26915	8
horen	2.766	2.38	33173	9626	7
mogen	2.504	1.73	30131	7089	3
voelen	3.132	2.28	29234	13955	7
stellen	2.549	2.14	27078	5094	7
leven	0.411	1.33	26762	1869	4
vallen	3.279	2.1	26001	8189	16

spreken	2.416	2.21	25142	6084	6
volgen	2.67	2.21	21720	2903	7
kennen	2.433	2.45	21514	4651	4
trekken	2.572	2.39	20145	9038	15
blijken	3.076	1.91	19597	7395	1
noemen	2.939	1.82	18351	2567	2
leggen	2.564	2.24	18068	6125	5
schrijven	2.7	2.04	17958	5206	6
halen	2.092	2.3	17748	5915	3
zetten	2.211	1.87	17652	5612	4
spelen	1.87	2.25	16115	2732	11
roepen	3.348	2.21	15111	8238	4
wachten	1.358	2.06	14839	3132	3
leren	1.765	2.13	14686	1345	2
praten	1.126	1.92	14570	1348	3
zoeken	2.065	2.41	13945	2955	4
slaan	2.936	1.69	13752	5790	10
lezen	1.848	2.44	12834	2573	5
lachen	2.234	2.27	12773	4890	1
dragen	2.512	1.96	11963	4064	6
helpen	1.567	2.39	11749	1533	5
hangen	2.654	2.34	11746	3940	8
dienen	2.482	2.18	11429	1467	7
leiden	2.463	2.26	10955	2219	6
steken	3.154	1.23	10772	5576	11
wijzen	3.367	2.12	10582	5051	5
hoeven	2.952	1.23	10197	2229	2
draaien	2.907	2.07	9850	5150	11
schijnen	3.897	2.39	9770	4306	2
raken	2.019	2.48	9419	2642	6
merken	2.535	1.92	9381	3417	2
wonen	2.211	2.2	9026	2210	1
slapen	2.129	2.01	8739	1595	5
rijden	2.826	2.34	8591	2822	4
sluiten	3.383	2.4	8351	2638	8
richten	3.025	2.49	8289	1774	7
eten	1.001	2.18	8283	644	1
klinken	3.929	2.18	8091	4219	5
heten	3.593	1.58	7793	2193	1
bieden	2.264	1.65	7689	1418	4

zorgen	1.669	1.76	7608	894	2
kiezen	2.662	1.94	7555	914	3
lijden	4.113	1.78	7188	1381	3
pakken	2.307	2.13	7159	3295	12
voeren	2.074	2.16	7087	1223	8
knikken	5.014	1.74	6986	5355	4
kopen	2.169	1.31	6942	981	1
menen	3.328	2.28	6839	2515	4
drinken	1.961	2.29	6784	1846	2
schieten	2.808	1.48	6642	3450	5
drukken	3.784	2.14	6555	3552	8
sterven	2.226	2.39	6524	1255	3
tonen	2.811	2.44	5565	1351	5
hopen	3.842	2.2	5399	1358	3
durven	2.566	2.05	5336	1827	1
schudden	3.744	1.98	5241	3586	2
zwijgen	1.838	2.2	5191	1771	2
dringen	2.542	1.61	5164	1828	3
springen	2.728	2.37	5030	2927	5
werpen	3.151	1.55	4882	2242	3
treden	1.674	2.33	4873	883	3
breken	3.081	2.27	4762	1327	9
stoppen	2.619	2.29	4691	1702	8
gooien	2.851	2.1	4594	1606	1
schreeuwen	2.679	2.25	4585	2239	6
huilen	1.424	2.19	4580	958	2
trachten	2.301	1.89	4477	1100	1
schuiven	3.34	1.77	4401	2063	4
kloppen	2.937	2.37	4350	1341	6
bellen	2.623	2.24	4292	1442	4
sturen	2.926	2.29	4284	987	5
zingen	1.844	2.26	4234	845	3
vliegen	2.061	2.15	4232	1184	6
grijpen	3.104	2.21	4155	3601	2
staren	2.855	2.22	4113	2213	1
missen	2.955	2.24	4093	642	4
wensen	2.721	2.08	4017	1041	2
trouwen	3.052	2.35	4006	421	3
bouwen	2.703	2.54	3971	300	2
voegen	2.731	2.03	3866	1729	5

treffen	3.103	1.96	3840	954	5
schenken	3.074	2.25	3745	1360	3
rennen	2.45	2.35	3707	1714	1
schrikken	4.311	1.7	3622	1339	3
kosten	1.342	1.67	3566	915	2
dwingen	3.505	2.32	3451	683	2
vangen	2.929	1.76	3435	467	5
winnen	2.386	2.08	3383	511	6
drijven	3.004	2.19	3360	958	7
scheppen	1.256	2.1	3344	353	4
stijgen	2.896	1.95	3335	1175	3
duwen	3.449	1.35	3288	1738	3
vullen	2.799	1.36	3245	830	2
buigen	4.331	1.74	3234	2865	5
delen	3.119	1.96	3233	782	5
glijden	1.878	1.91	3193	1260	1
wekken	2.378	2.23	3171	538	2
redden	2.242	2.24	3076	140	2
letten	3.008	1.92	3053	374	3
dreigen	3.217	1.81	2903	837	2
zakken	2.104	1.2	2849	877	6
kruipen	2.515	1.95	2836	1019	5
dromen	2.464	1.93	2786	645	3
branden	2.951	1.53	2769	709	6
snijden	2.597	1.72	2682	558	10
vechten	2.032	2.15	2651	1224	4
wenden	4.183	1.98	2613	1397	3
varen	3.545	2.38	2550	838	3
wagen	0.71	1.87	2533	347	2
heersen	3.115	2.2	2511	773	3
koken	1.969	1.89	2436	177	4
spijten	6.367	2.05	2433	255	1
zuchten	4.008	1.31	2420	1754	3
kussen	2.798	2.13	2365	1293	1
zwaaien	2.826	1.7	2347	983	3
dalen	2.098	1.95	2332	562	3
wennen	3.946	1.99	2297	59	3
heffen		0.6	2283	1092	2
vrezen	3.542	1.48	2279	604	3
trillen	1.737	2.26	2278	492	3

eisen	1.424	2.34	2271	522	2
kleden	3.935	2.37	2227	465	3
danken	3.318	0.98	2222	154	3
jagen	2.052	2.25	2168	461	5
spannen	4.866	1.99	2165	320	4
streven	0.941	2.12	2147	137	1
klimmen	2.313	2.25	2095	723	2
slikken	1.953	1.49	2086	603	2
leunen	4.163	1.52	2083	1212	2
scheiden	3.372	1.59	2039	199	7
stemmen	3.472	0.89	2028	561	4
schikken	5.591	1.84	2024	180	5
wrijven	2.842	2.45	2022	1073	4
binden	4.164	2.24	1979	727	10
strelen	2.76	1.84	1961	971	2
strekken	2.705	1.04	1956	758	4
duiken	2.969	1.02	1955	794	4
vatten	2.657	0.63	1854	339	3
storten	2.457	2.14	1846	543	7
vluchten	3.134	1.27	1836	380	2
bijten	2.583	2.19	1829	930	3
stoten	2.393	2.28	1784	691	10
bidden	2.785	2.45	1782	1316	4
vegen	2.967	1.88	1760	973	3
zenden	2.921	2.09	1752	457	1
blazen	2.794	1.59	1737	703	4
stelen	3.502	2.05	1621	617	1
barsten	2.55	2.16	1602	612	3
rijzen	3.169	2.21	1592	290	4
meten	2.695	2.21	1585	548	3
zwemmen	1.092	1.85	1567	241	1
liegen	2.417	2.35	1554	296	2
klagen	1.885	2.03	1544	328	2
gillen	2.455	2.15	1540	625	3
wijden	2.609	1.84	1485	247	3
knijpen	3.269	2.11	1479	847	1
scheuren	2.777	2.09	1476	416	7
drogen	3.525	2.28	1469	174	2
voeden	2.249	2.31	1466	88	6
schatten	2.922	2.36	1430	242	2

smeken	2.933	1.06	1420	490	1
stichten	3.526	2.15	1412	129	2
storen	3.158	2.2	1391	166	2
beven	1.837	1.55	1381	331	2
stralen	2.043	1.54	1375	432	4
slepen	2.672	1.74	1371	379	3
strijken	4.143	2.29	4712	2913	8
wegen	0.924	1.02	1328	321	3
zuigen	2.147	1.58	1312	394	5
vloeien	2.365	2.22	1308	255	2
spotten	3.815	2.32	1249	122	4
schamen	2.45	1.96	1216	426	1
zweven	2.097	2.35	1205	385	2
schuilen	6.287	2.07	11295	8565	2
snappen	3.948	1.43	1125	159	3
glimmen	2.942	2.27	1124	184	2
brullen	2.865	2.03	1116	588	4
schelen	0.874	1.96	1115	177	3
fluiten	2.156	1.89	1097	326	5
grommen	3.324	1.89	1086	606	2
vergen	2.705	2.05	1068	131	1
schetsen	2.797	1.67	1066	81	2
stinken	3.106	1.91	1064	282	1
hollen	3.229	1.98	1045	383	1
wuiven	2.98	2.05	1030	495	2
gloeien	2.071	2.03	1000	199	3
prijzen	2.723	1.48	63	0	2
gieten	2.786	2.06	980	418	4
smijten	3.549	2.24	947	399	1
sluipen	2.951	1.97	925	495	1
wijken	5.289	1.82	14024	6931	3
strijden	5.353	0.73	845	60	3
snikken	1.536	2.11	827	214	1
snuiven	3.349	1.92	826	457	3
smelten	2.213	1.72	816	100	4
zinken	2.014	2.3	786	258	1
spuiten	2.657	2.15	779	263	9
zoenen	2.909	2.21	768	258	1
zweren	2.666	1.73	91	7	5
scheren	2.421	1.92	718	63	4

doemen	3.874	1.7	715	115	1
breien	2.614	2.12	705	45	1
druipen	3.164	1.61	705	260	1
krabben	1.904	1.48	704	258	1
zwerven	2.178	1.97	692	155	2
wringen	2.833	2.37	669	341	3
spoelen	2.264	2.41	668	219	4
blinken	2.368	2.21	667	134	1
schelden	1.635	2.39	659	173	1
graven	2.182	2.15	653	127	1
zweten	3.501	2.31	644	124	2
vellen	3.228	2.12	626	219	2
stikken	2.046	1.01	610	112	4
hijsen	3.352	2.11	594	466	2
zeuren	1.555	2.41	589	81	1
krimpen	2.769	1.99	573	200	2
vreten	1.424	2.36	555	92	5
sleuren	3.453	2.33	548	170	1
vriezen	3.761	2.1	482	91	2
delven	3.487	2.27	479	62	2
spugen	2.599	1.87	436	105	3
wreken	1.519	1.74	431	30	3
splitsen	2.367	2.43	427	37	3
zeilen	1.662	1.91	417	113	2
stuiven	3.814	1.85	403	220	2
mikken	2.43	2.05	323	104	3
vlechten	2.381	1.42	320	36	1
vleien	4.189	2.01	320	76	2
slijten	1.951	2.32	310	65	5
mijden	2.352	1.32	272	45	1
rijmen	1.685	2.11	256	24	4
splijten	5.082	1.95	768	291	2
zuipen	1.689	2.26	237	35	2
slachten	5.049	0.38	229	23	1
slijpen	4.502	1.59	229	85	4
schroeven	1.726	2.22	226	98	1
schrijden	3.874	1.85	221	108	1
porren	3.465	2.39	180	77	2
pissen	1.855	2.28	176	48	2
snoeren	2.541	1.95	174	31	1

snuiten	2.799	1.54	173	75	2
waden	4.818	0.9	171	55	1
werven	1.945	1.91	167	14	2
rijgen	5.889	0.58	136	14	3
zwieren	3.554	1.97	128	39	2
schaven	2.638	2.04	120	17	6
schijten	2.668	2.17	119	72	1
hikken	4.101	1.74	116	44	1
houwen	4.607	1.34	92	6	2
sprinten	2.617	1.77	90	30	1
spruiten	1.797	2.06	82	19	2
pluizen	2.173	1.6	55	15	2

Appendix D. Attention Based on Information Maximization Script

1. Bruce, N.D.B., Tsotsos, J.K., Saliency, Attention, and Visual Search: An Information Theoretic Approach, Journal of Vision 9:3, pp.1-24, 2009, http://journalofvision.org/9/3/5/, doi:10.1167/9.3.5.
2. Bruce, N.D.B., Tsotsos, J.K., Saliency based on Information Maximization. Advances in Neural Information Processing Systems, 18.
3. Bruce, N. Features that draw visual attention: An information theoretic perspective. Neurocomputing, v. 65-66, pp. 125-133, May 2005.

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ATTENTION based on INFORMATION MAXIMIZATION
MODEL OF ATTENTION BASED ON INFORMATION MAXIMIZATION
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***************************************************
FOR ADDITIONAL REFERENCES AND SOME TIPS SPECIFIC TO USING
THE SOFTWARE FOR PSYCHOPHYSICS STIMULI, SEE THE END OF THIS
FILE - IN ADDITION, SOME FUNCTIONALITY MAY REQUIRE FILES
NOT INCLUDED IN THE "BASIC" DISTRIBUTION, PLEASE CONTACT
THE AUTHOR FOR SUCH QUERIES, OR FOR ADDITIONAL COMMENTS AND
BUGS. USE OF THIS SOFTWARE IS SUBJECT TO THE COPYRIGHT
NOTICE APPEARING AT THE BOTTOM OF THIS FILE
There is a single required argument which is the image
name, however there are additional arguments which may
slightly alter the behavior since many of these require
different sub-arguments they require editing the parameters
in the code itself, that said, there are a few parameters
that are directly accessible from the command line:

Use:
function infomap =
AIM(filename,resizesize,convolve,thebasis,showoutput);
Basic usage: out = AIM(imagename); optional arguments are:
out = AIM(imagename,resizesize,convolve,basisname,output);
resizesize - A scaling factor (% original image size)
convolve - convolve the output with a gaussian?
```

```
basisname - the feature set e.g. 21jade950, 31infomax975
The latter 3 digits correspond to the variance retained in
PCA which precedes the ICA method named.
output - show some visualization. This may require changing
some parameters appearing in the code depending on the
desired "look".
e.g. b = AIM('23.jpg',0.5,1,'21jade950.mat',1);
Additional options are specified in the parameters that
follow including the ability to modify parameters of the
computation not available on the command line.
% Set to defaults or input values nargs = nargin; if nargs
< 2, resizesize=1.0; end if nargs < 3, convolve=0; end
if nargs < 4, thebasis='21jade950.mat'; end %others are
e.g. 31jade900, 21infomax950 etc. if nargs < 5, showoutput
= 0; end % Non command-line Defaults - require manual
change
% For convolve = 1 set these sigval = 8; % How many pixels
correspond to 1 degree visual angle
GENERAL SETUP
sigwin = [30 30]; % What size of window is needed to
contain the above
SPECIFY METHOD FOR DENSITY ESTIMATION method = 1; %
PARAMETERS FOR METHOD 1 bins = 1000;
% PARAMETERS FOR METHOD 2 sigma = 0.01; precision = 0.01; %
% %
% PARAMETERS FOR METHOD 3 ONLY psi =
fspecial('gaussian',49,20); psi
SCALING TYPE
Careful, sigma is variance not std. dev. Precision fixed at
0.01 for now Parameters of Parzen estimate
% Local interaction entirely specified by
% Filter dimensions must be odd % This involves local
surround % suppression so size of the kernel % depends on
scale unlike the previous % methods
scalingtype = 2; % % % % % % %
across
PROCESSING
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Read image fprintf('Reading Image.\n'); inimage =
(imresize(im2double((imread(filename))),resizesize));
% Load basis fprintf('Loading Basis.\n'); load(thebasis);
```

```
For density estimate, histogram, or Parzen estimate Created
with a minimum and maximum value within certain bounds and
for a particular precision - these bounds may be determined
by the maximum and minimum values across all features (type
1) or within each feature domain (type 2) or additionally
as in type 2 but based on learned values from a large
number of exemplars
several images (type 3) - type 3 are loaded from a file
% Output related % For showoutput=1 dispthresh = 80; %
threshold contrastval = 6; % %%%% END OF DEFAULT VALUES
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
How much is the cutoff percentage wise in the hard How much
contrast in the "transparent" representation
inbasis=B;     % B should be the variable holding the
unmixing matrix % Be careful of which one is being used and
choose
%inbasis=pinv(B)'; % appropriately which may involving
uncommenting this line
% depending on how you store your learned basis % functions
% Some values precomputed for efficiency p =
sqrt(size(inbasis,2)/3); pm = p-1; ph = pm/2; % These two
lines assume an odd window size
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% If starting with mixing matrix may need pseudoinverse
else leave as is pv = inbasis;
fprintf('Projecting local neighbourhoods into basis
space.\n'); progress = 0; fprintf('0    25   50   75
     100\n');
for i=ph+1:size(inimage,1)-ph
% A progress indicator for impatient people ;) progress =
progress + 1/(size(inimage,1)-pm); if (progress > 0.025)
progress = progress - 0.025;
fprintf('.') end
for j=ph+1:size(inimage,2)-ph
% Build a pxp patch [in column vector form] around the
local % coordinate
t = inimage(i-ph:i+ph,j-ph:j+ph,:); temppatch = t(:)';
% Project patch onto basis BVpatch=pv*(temppatch)';
PRODUCE SPARSE REPRESENTATION OF IMAGE CONTENT
%%%%%% %%%%%% %%%%%%
end
```

```
clear temppatch % Garbage collection
% Now add a pixel to each of the 3*patchsize^2 new feature
maps s(:,i-ph,j-ph)=BVpatch';
clear BVpatch % Garbage collection end
% Rescale for efficient density estimation - this grabs
values across all % of the "independent" feature
dimenstions - individual scaling may apply % later
depending on parameters specified
minscale = min(min(min(s))); maxscale = max(max(max(s)));
fprintf('\nPerforming Density Estimation.\n');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
progress = 0; fprintf('0 25   50   75   100\n');
for z=1:size(s,1)
% A progress indicator for impatient people ;) progress =
progress + 1/size(s,1); if (progress > 0.025) progress =
progress - 0.025;
fprintf('.') end
% Translate image from 1xMxN to MxN for ease of processing
tempim(1:size(inimage,1)-pm,1:size(inimage,2)-pm) =
s(z,1:size(inimage, 1)-pm,1:size(inimage,2)-pm);
% If scaling based on values from all feature dimensions,
reset for each % feature domain if (scalingtype == 1)
% Do nothing, already got the min and max across all
dimensions from s
% above end
COMPUTE FEATURE LIKELIHOOD BASED ON A DENSITY ESTIMATE
%%%%%% %%%%%% %%%%%%
if (scalingtype == 2) % Scale each domain between 0 and 1
separately minscale = min(min(tempim)); maxscale =
max(max(tempim));
end
if (scalingtype == 3) % load learned limits for various
basis functions - scaling method 3 only % load
minmax31jade900
load minmax21jade950 % load thelimits
minscale = minval(z); % If scaling based on a learned
representation of ranges from natural image content
maxscale = maxval(z); % Note you must load a ranges
variable with maxes and mins for each dimension
end
% Scale temporary copy of feature plane stempim = tempim-
```

```
minscale; stempim = stempim./(maxscale-minscale);
% This next line can be dangerous - only applies in case 3
if (scalingtype == 3) stempim = max(stempim,0); stempim =
min(stempim,1);
end
if (method == 1) %%% METHOD 1 - HISTOGRAM ESTIMATE OVER
ENTIRE IMAGE
%Compute histogram histo = imhist(stempim,bins);
% Rescale values based on histogram to reflect likelihood
ts(z,:,:) = histo(round(stempim*(bins-1)+1))./sum(histo);
elseif (method == 2) %%% METHOD 2 - NON-PARAMETRIC ESTIMATE
OVER ENTIRE IMAGE
% Compute non-parametric density estimate dens =
kernest(stempim(:),sigma,precision); %dens =
dens./sum(sum(dens));
% Re-map values based on probabilities % Precision fixed at
100 for the moment
ts(z,:,:) = dens(round((stempim*99+1)));
elseif (method == 3) %%% METHOD 3 - NON-PARAMETRIC ESTIMATE
OVER LOCAL NEIGHBORHOOD %%% THIS IMPLEMENTS THE FULL
CIRCUIT METHOD LOCALLY USING THE PSI %%% PARAMETER - THIS
IS COMPUTATIONALLY INTENSIVE BUT MIGHT BE MOST ACCURATE %%%
FROM THE PERSPECTIVE OF BIOLOGICAL PLAUSIBILITY
% Psi indicates the contribution of neighbouring elements
to the local % estimate as in [1].
% To deal with edge effects, the external portion of the
image is reflected % about the image boundary, so that the
estimate is effectively based on % support from one side
only
halfsupport = (size(psi,1)-1)/2;
% Add support region to image rstempim =
ones(size(stempim,1)+size(psi,1)-
1,size(stempim,2)+size(psi, 2)-1);
%rstempim(halfsupport+1:size(rstempim,1)-
halfsupport,halfsupport+1:size (rstempim,2)-
halfsupport)=stempim;
% And reflect inside region rstempim =
padarray(tempim,[halfsupport
halfsupport],'both','symmetric');
nor = 1/(sqrt(2*pi)*sigma); % Normalize the kernel
for xx=halfsupport+1:size(rstempim,1)-halfsupport for
```

```
yy=halfsupport+1:size(rstempim,2)-halfsupport
ts(z,xx-halfsupport,yy-halfsupport)=nor*sum(sum(psi.*exp(-
(rstempim (xx-halfsupport:xx+halfsupport,yy-
halfsupport:yy+halfsupport)-rstempim
(xx,yy)).^2/(2*sigma^2))));
end
end end end fprintf('\nTransforming likelihoods into
information measures.\n');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
TRANSFORMATION INTO THE INFORMATION DOMAIN
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Overall information content is product of individual
feature maps with % Shannon definition of Self-Information
applied - Can do a log of products % or a sum of logs...
the former requires too much precision
% When information is being added, tasks specific weights
can be introduced % for each channel allowing top down bias
% Width and height of information map wid = size(ts,2); hei
= size(ts,3);
% Initialize to information gained from 1st feature domain
infomapt = -log(reshape(ts(1,:,:),wid,hei)+0.000001);
% Add information gained from remaining features for
z=2:size(s,1) %for z=2:50 infomapt = infomapt -
log(reshape(ts(z,:,:),wid,hei)+0.000001); end
if (convolve == 1) infomapt =
filter2(fspecial('gaussian',sigwin,sigval),infomapt);
end
% Pad the final map so that its size matches the input
image
infomap =
zeros(size(inimage,1),size(inimage,2))+min(min(infomapt));
%size(infomap(ph+1:size(inimage,1)-ph,ph+1:size(inimage,2)-
ph)) %size(infomapt) infomap(ph+1:size(inimage,1)-
ph,ph+1:size(inimage,2)-ph)=infomapt;
tempim = zeros(size(inimage));
if (showoutput == 1) figure
subplot(2,2,1) imshow(inimage,[]) subplot(2,2,2)
imshow(infomap(sigwin(1):size(infomap,1)-
sigwin(1),sigwin(1):size
(infomap,2)-sigwin(1)),[]); subplot(2,2,3) threshmap2 =
min((infomap./prctile(infomap(:),98)),1);
```

```
r=imshow(inimage,[]);
set(r,'AlphaData',threshmap2.^contrastval);
subplot(2,2,4) threshmap1=(infomap >
prctile(infomap(:),dispthresh));
tempim(:,:,1)=threshmap1.*inimage(:,:,1);
tempim(:,:,2)=threshmap1.*inimage(:,:,2);
tempim(:,:,3)=threshmap1.*inimage(:,:,3);
imshow(tempim,[]);
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
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SAMENVATTING IN HET NEDERLANDS

Dit proefschrift biedt een perspectief op woordvindingsproblemen bij mensen met taalstoornissen. Gemiddeld heeft iemand een woordenschat van zo'n 50000 woorden (Crystal, 2008). Normaal gesproken raadplegen we dit zogeheten lexicon met ongelofelijke snelheid en accuraatheid tijdens het spreken. Af en toe gebeurt het ook bij gezonde volwassenen dat een verkeerd woord geselecteerd wordt ("Ik moet niet teveel rijden; ik moet nog drinken."). Bij volwassenen met een verworven taalstoornis (afasie) en kinderen aangeboren taalstoornis (ESM: ernstige spraak/en of taal moeilijkheden) gebeurt dit echter zo vaak dat het de communicatie ernstig belemmert. Een vraag die binnen de wetenschap nog onbeantwoord is, is of bij personen met taalstoornissen deze woorden niet (meer) aanwezig zijn in het lexicon; of dat het zoekmechanisme dat het correcte woord moet selecteren en ophalen niet goed (meer) werkt. Dit proefschrift levert bewijs voor de laatste visie en biedt een nieuwe theoretische benadering omtrent de rol van verwerkingscapaciteit binnen woordvindingsproblemen. Hiervoor wordt gebruikt gemaakt van een aantal begrippen en formules uit de *informatietheorie*.

In hoofdstuk 1 worden de belangrijkste begrippen uit de informatietheorie uiteengezet. Informatietheorie is een wiskundige theorie die zich bezighoudt met kansberekeningen, chaos en onzekerheid. Binnen de wetenschap van de communicatie wordt Claude Shannon gezien als één van de grondleggers voor de toepassing van informatietheorie op het overdragen van informatie via (technische) kanalen. In 1948 publiceerde hij een artikel waarin hij verklaart hoe ruis de oorzaak kan zijn van de vervorming van boodschappen die verzonden worden vanaf de grond naar vliegtuigen in de lucht tijdens de 2e wereldoorlog. Cruciaal hierbij is dat hij aantoont dat *ieder* (technisch) kanaal een bepaalde maximale kanaalcapaciteit heeft. Zodra deze capaciteit ontoereikend is, m.a.w. zodra de complexiteit van de te verzenden boodschap te hoog is, ontstaan er fouten in de verzonden boodschap. De complexiteit van de te verzenden boodschap meet hij in *bits* (binary digits) en de kanaalcapaciteit geeft dus weer hoeveel bits per seconde een bepaald kanaal foutloos kan verzenden.

Sinds de publicatie van Shannon's werk is informatietheorie niet alleen uitgebreid toegepast in onderzoek naar communicatie, maar ook in (psycho)linguïstisch onderzoek zien we de benadering steeds vaker opduiken. De benadering wordt met name gebruikt om linguïstische eenheden te voorzien van een complexiteitsmaat. In het algemeen geldt: hoe hoger de complexiteit van een lexicaal item, of een linguïstische structuur (gemeten in bits), hoe meer verwerkingscapaciteit nodig is om ze te verwerken. De overkoepelende hypothese van dit proefschrift is dat mensen met een taalstoornis te maken hebben met een verminderde verwerkingscapaciteit. Ik presenteer bewijs hiervoor aan de hand van een aantal experimenten en analyses van spontane taal van mensen met een taalstoornis, waarbij ik constant gebruik maak van een informatietheoretische benadering om lexicale items van een complexiteitsmaat te voorzien. Zoals uit de resultaten blijkt, levert dit proefschrift bewijs dat mensen met een taalstoornis moeite hebben met het verwerken van meer complexe lexicale eenheden, gemeten aan de hand van een aantal informatie theoretische maten.

Deel A

Het eerste deel van dit proefschrift (deel A) biedt een informatietheoretische benadering voor het ophalen van werkwoorden uit het lexicon bij mensen met een afasie. Hierbij wordt informatietheorie gebruikt om individuele lexicale items (vervoegde werkwoorden), alsmede de paradigmatische familie waartoe de vervoegde vorm behoort te voorzien van een complexiteitsmaat. In hoofdstuk 2 test ik in hoeverre deze twee maten voorspellers zijn van de reactietijd in een auditief aangeboden lexicaal decisie experiment bij een groep gezonde jongeren en een groep gezonde ouderen. In dit experiment horen (auditief) deelnemers een woord (lexicaal) en moeten zij aan de hand van een druk op de knop (ja / nee) aangeven of dit een bestaand Nederlands woord is of niet (decisie). Aangenomen wordt dat de snelheid waarmee proefpersonen op de knop drukken een weergave is van de tijd die nodig is om het woord te verwerken (cf. Millberg & Blumstein, 1981). Naast deze 2 informatietheoretische factoren worden ook meer traditionele voorspellers meegenomen, zoals woordfrequentie. De resultaten van dit hoofdstuk laten zien dat de twee geïntroduceerde complexiteitsmaten beide een significante invloed hebben op de verwerkingssnelheid van vervoegde werkwoordsvormen. Een belangrijke uitkomst van dit experiment is dat er vrijwel geen verschil is in de resultaten voor de jongere en oudere deelnemers. Dit feit wordt geïnterpreteerd als bewijs dat lexicale activatie en de structuur van het lexicon niet wezenlijk veranderen naarmate het brein veroudert.

In hoofdstuk 3 wordt vervolgens dezelfde taak aangeboden aan een groep patiënten met afasie. Het experiment is goed uitvoerbaar voor de afatische deelnemers; zij scoren rond de 85% correct. De groep gezonde ouderen die aan deze groep afatici gematched is op leeftijd en opleidingsniveau scoort 94% correct. Het feit dat de afatici goed kunnen aangeven of een gehoord woord een bestaand woord is of niet, geeft aan dat de lexicale items aanwezig zijn in hun lexicon. Vervolgens zijn de reactietijden op dit experiment bekeken aan de hand van dezelfde factoren als in hoofdstuk 2. Uit de resultaten blijkt, en dat is niet verrassend, dat de afatici over het algemeen wat trager zijn dan de gezonde proefpersonen. Belangrijker is, dat dit hoofdstuk laat zien dat de dezelfde factoren die van invloed zijn op de verwerkingssnelheid bij gezonde volwassen, op dezelfde manier van invloed zijn op de verwerkingssnelheid bij de afatici. Met andere woorden, als een woord hoogfrequent is (heel vaak voorkomt), drukken zowel de controle proefpersonen als de afatische deelnemers sneller op de JA-knop, dan wanneer een woord laagfrequent is. De resultaten van de afatici verschillen in de mate waarin de informatietheoretische factoren van invloed zijn op de reactietijden. Mensen met afasie hebben onevenredig meer moeite met de lexicale items die een hoge complexiteit hebben volgens de informatie theoretische maten. Met andere woorden, deze resultaten geven aan dat de verwerkingscapaciteit van deze deelnemers gereduceerd is. Op het moment dat complexiteit systematisch gemanipuleerd wordt, treden er significante verschillen op tussen de afatici en de controle proefpersonen.

In hoofdstuk 4 wordt vervolgens bekeken of deze gereduceerde verwerkingscapaciteit ook een rol speelt in niet-talige verwerking. Afasie wordt traditioneel immers gezien als een pure taalstoornis, waarbij andere cognitieve vaardigheden relatief onaangedaan zouden moeten zijn. Dit hoofdstuk beschrijft een visuele zoektaak, waarbij de deelnemer gevraagd wordt om te kijken naar een plaatje met een aantal stippen en aan te geven of er in het plaatje een afwijkende stip aanwezig is. De doel-stip is aanwezig in de helft van de gevallen en de grootte wijkt in meer of mindere mate af van de andere stippen. In de helft van de gevallen is de stip bijna de helft kleiner dan de andere stippen en valt dus behoorlijk op. In de andere helft van de gevallen is de afwijkende stip slechts 30% kleiner dan de andere stippen en is daarmee een stuk lastiger te onderscheiden van zijn buurstippen. Naast het formaat van de stip is ook het aantal stippen per plaatje gevarieerd: 9 of 16 stippen. De mate waarin de doelstip te onderscheiden is van de buurstippen is berekend aan de hand van een informatietheoretisch model. Zo heeft ieder plaatje dus een eigen complexiteitsmaat.

De resultaten van dit onderzoek laten zien dat op de makkelijke plaatjes (9 stippen en een erg afwijkende doelstip) afatische deelnemers net zo snel en accuraat zijn in het spotten van de doelstip. Ook als er geen doelstip is (NEE-knop), is er geen verschil tussen de reactietijden van de afatische deelnemers en de gezonde ouderen. Wanneer echter de complexiteit van het plaatje gemanipuleerd wordt, door de doel-stip moeilijk onderscheidend te maken (maar een klein beetje kleiner dan de anderen), is er een significant verschil tussen de reactietijden van de afatische en controle deelnemers. Hoofdstuk 4 levert dus bewijs dat de gereduceerde verwerkingscapaciteit niet alleen evident is in talige taken voor afatische deelnemers, maar dat bij de juiste manipulatie van de stimuli aan de hand van een informatie theoretisch model, ook niet-talige taken lastiger blijken te zijn.

Deel B.

Het tweede deel van dit proefschrift (deel B) bevat 2 hoofdstukken waarin spontante taal gebruikt wordt om verder te onderzoeken of informatietheorie een zinvol hulpmiddel is in onderzoek naar verwerkingscapaciteit bij taalgestoorde mensen. Hoofdstuk 5 maakt gebruik van een tweede informatie theoretische benadering: de relatie tussen Zipf's wet en verwerkingscapaciteit in afatische sprekers. In hoofdstuk 6 wordt de productie van lidwoorden van zowel afatische sprekers als kinderen met ESM onderzocht binnen een informatie theoretisch kader.

Hoofdstuk 5

In dit hoofdstuk onderzoek ik de spontane taalsamples van 4 afatische sprekers aan de hand van de wet van Zipf (Zipf, 1949). George Kingsley Zipf bestudeerde lange teksten en vond dat als je alle woorden uit een tekst ordent naar frequentie en vervolgens ieder woord voorziet van een rangnummer, dat het meest voorkomende woord twee keer zo vaak voorkomt als het op één na frequentste; drie maal zo vaak als het derde in de rij, enzovoort. Als je deze frequenties en rangordes in een log-log-grafiek uitzet, dan krijg je een rechte lijn met een bepaalde hoek. Deze wetmatigheid staat bekend als de wet van Zipf. Ferrer i Cancho heeft vervolgens verschillende geschreven en gesproken teksten gebruikt om te onderzoeken *waarom* deze wetmatigheid voorkomt en of de hoek van de grafiek een betekenisvolle rol speelt. Hij stelt voor dat de wet van Zipf een direct resultaat is van het "principle of least effort". Daarmee bedoelt hij dat voor sprekers het meest efficiënt zou zijn (en dus de minste moeite zou kosten) om voor alle concepten in de wereld slechts 1 woord te gebruiken. Het zoeken in het lexicon naar de juiste representatie voor een bepaald voorwerp zou hierdoor supersnel gaan, aangezien het lexicon slechts uit 1 representatie bestaat. Voor de *luisteraar* is dit echter helemaal niet efficiënt. Het wordt op deze manier onmogelijk de spreker te begrijpen. De luisteraar heeft bij voorkeur een unieke representatie voor ieder concept in de wereld. Volgens Ferrer i Cancho is de wet van Zipf een weergave van dit evolutionaire spanningsveld tussen spreker en luisteraar. Bovendien is een vergelijkbaar spanningsveld nog steeds evident in communicatie. Op ieder moment is communicatie te vangen met de volgende formule:

$$\Omega = I - H$$

waarbij I staat voor de over te brengen boodschap, en H voor de cognitieve prijs die dit kost. Voor een individuele spreker is de wet van Zipf een weergave van dit spanningsveld.

Voor gezonde sprekers geldt dat de balans tussen het overbrengen van de boodschap en de moeite die dit kost altijd ongeveer gelijk is. De hoek van de grafiek die ontstaat als een resultaat van Zipf's wet (uitgedrukt in *ß)* is ongeveer 2. Voor groepen met een mogelijk afwijkende balans zou de hoek anders kunnen zijn. Ferrer i Cancho (2006) vindt bijvoorbeeld afwijkende waarden voor de hoek van de grafiek voor hele jonge kinderen (*ß*= 1.5) en voor mensen met schizofrenie (*ß*=3). In hoofdstuk 5 laat ik zien dat de hoek van de grafiek die ontstaat uit de wet van Zipf voor afatische sprekers anders is dan voor gematchte gezonde sprekers. Ik interpreteer deze bevindingen als een bewijs voor een verschuiving in de balans tussen (I) en (H) in de bovenstaande formule. De boodschap die mensen met afasie over willen brengen (I) is onveranderd. Maar door hun hersenletsel, hebben de afatische sprekers minder vermogen (H) om een boodschap over te brengen. Het resultaat hiervan is dat de balans tussen I en H dus verschuift en de grafiek een andere hoek krijgt. Dit hoofdstuk levert dus meer bewijs voor een verminderde verwerkingscapaciteit in afasie met een relatief intact lexicon.

Hoofdstuk 6 maakt gebruik van spontane spraak van 2 groepen sprekers met taalstoornissen: een groep volwassenen met afasie en een groep kinderen met ESM. In dit hoofdstuk bekijk ik de productie van lidwoorden binnen een informatietheoretische benadering. Voor zowel kinderen met ESM als (niet-vloeiende) afatische sprekers is het bekend dat woorden uit de gesloten klassen (voorzetsels; persoonlijke voornaamwoorden; lidwoorden) erg lastig zijn. In dit hoofdstuk bekijk ik of het ontstaan van de problemen in de productie van lidwoorden voor beide groepen uit te leggen is met een eenduidige verklaring. Hierbij maak ik gebruik van de notie "kanaalcapaciteit" uit de informatie theorie en stel ik voor om de relatie tussen zelfstandige naamwoorden en hun bijbehorende lidwoorden te zien als een 'kanaal'. Bij het ophalen van een lidwoord "stuurt" het zelfstandige naamwoord informatie over aantal, gender en definietheid naar de set van lidwoorden die bestaat in het Nederlands (de, het en een) en aan de hand van deze informatie wordt het correcte lidwoord geselecteerd. Ik laat in hoofdstuk 6 zien dat er een correlatie is voor jonge gezonde kinderen en kinderen met ESM tussen de mate van verstoring in dit kanaal en het percentage omissies van lidwoorden in spontane spraak. Hoe groter de verstoring in het kanaal, hoe vaker het kind verzuimt een lidwoord te produceren. Voor de afatici vinden we echter een ander patroon. Hier lijkt de complexiteit van het *individuele lidwoord* een belangrijker voorspeller voor het omissiepercentage te zijn dan de verwerkingscapaciteit van het voorgestelde kanaal. Het lijkt er dus op dat het in dit hoofdstuk voorgestelde model een weergave is van een maturatieproces en niet zozeer ten grondslag ligt aan de taalstoornis die beide groepen delen.

In hoofdstuk 7 vat ik de resultaten van de voorgaande hoofdstukken samen en beargumenteer ik dat mensen met een afasie een gereduceerde verwerkingscapaciteit hebben. De resultaten uit dit proefschrift laten zien dat dit het geval is bij de verwerking van zowel talig als niet-talig materiaal. Binnen de taal lijkt de algehele structuur van het lexicon intact, maar zorgt een gereduceerde verwerkingscapaciteit voor een probleem in woordvinding naarmate de complexiteit van de lexicale representaties toeneemt. Informatietheorie is een zinvol kader gebleken om complexiteit van (linguïstisch) materiaal te kwantificeren en hiermee de verwerkingscapaciteit binnen taalstoornissen te onderzoeken.