Understanding bit by bit:

Information theory and the role of inflections in sentence processing

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Understanding bit by bit:

Information theory and the role of inflections in sentence processing

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Prof. dr. Sergey Avrutin

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To Z. & N.

Contents

P.S. I Thank You

A lot of times during the last year, I would walk around Utrecht and think about this part of the dissertation, especially after stressful periods that turned out to be quite nice because of the people that were next to me. Depending on the situation, I would re-write it, in my mind, starting always with "without you nothing of this would have been possible", with *you* referring to another person every time, in a situation-dependent manner, and it was always true. During these iterations I, once, concluded that it should be something like this:
"Eric, thank you.", and nothing more (blame it on the influence of minimalism...).

Because, however, this would only be an instantiation of my drama-queen nature and would not tell the whole story since there are many people that "without them nothing would have been possible", and because I love stories, in their long version, this morning, the very last morning of editing this dissertation, I will overcome the before-print fear of, say, misspelling my name in the front page (something like Sophia Maniak) and thank you all.

It is true. Without Eric, things would have been really different. Probably, I wouldn't have engaged in linguistics in the first place. We first talked when he called me, on a Sunday night, while Plushenko was closing the Figure-skating championship, to ask me why I applied for the MPhil program. I asked him: I like linguistics the way that I like dancing in bars. Is that enough?. He laughed and said: Well, that is how we know that we like something. Go for it. And that is what I did. Since then, Eric has been there, encouraging me at each point of research and life, "protecting" the string that connects me to the study of language, listening to my academic and personal considerations, helping me to discover all the puzzles that are out there ('puzzle': a very crucial word for Eric, and for me after all!), dealing with my panics and fears, lifting me up when I was down, being romantic (Sergey's term) about science

and willing to give me a whole explanatory lecture on any linguistic-related point of ignorance, no matter how trivial my question would be. Most importantly, he did all these, as if it was normal. Well, few people are like that. Eric, thank you. I really don't know what I would have done in linguistics if it weren't for you.

Another evening, while I was in Boston, feeling overwhelmed with all these knowledge and the difficult-to-process papers I run into a pretty nice one, that kept me in the office until late at night, inspired me and made me smile. I looked up the author and sent him a mail thanking him for writing such a nice thing in such an easy to understand way. Years later, when I applied for this project, I was told that this person would also like to supervise me and I got really happy because I thought it will be fun. Sergey, I still do not know if, in the end, you liked our working together or not. What I know is that it was pretty much the way I thought it would be: funny and inspiring meetings, critical and influential discussions. Thank you for coping with my unstable nature (I acknowledge that it was a hard league), for introducing me to physio-linguistics and supporting me all these years. I learned a lot and I enjoyed it even more.

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How would it be without Daria (Princess D) and Marko (The luv)? Daria and Marko, when I first met you, I couldn’t really follow the pace of the conversation. It was just too fast and too encoded. But I learned to “decipher” you, learned to communicate in Darkonese and that was the moment when the fun part started. Together with Loes we became the great four and that is one of the main factors that made my life in Utrecht be fun. Thank you for the days and evenings together, the laughs and the cuteness, the warmth and friendship you gave me. F.F.E.A.E. e? :)

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my family, the person who has criticized me and challenged me the *most*, has always (silently) believed in me, (effectively) helped me solve information-theoretical mysteries with spending hours on the beach drawing bars of “base-level of activation” on the sand, and married this fantastic person, Zoe, the woman I deeply love (and is “behind” the cover of this book), to make my luck even greater! And Manolito, I didn’t follow your advise to go on a world trip instead of going to Utrecht to study, and I think it is better that way, because this project is now completed, and because I very much appreciate you, your unconditional love and constant presence and support in every single rational or weird idea or desire I expressed all these years, this dissertation is dedicated to you. And to Nikos. You might not be able to understand it all, but maybe Nikos will help you clear things up a bit. Or maybe I will do. Smak.

CHAPTER 1

Introduction

1.1 Sentence comprehension

Understanding our mother tongue is natural, effortless. It feels like an easy task. However, what the brain masters in order to achieve this result is anything but trivial. Unlike what we might think, understanding language does not require simply matching of forms with meanings. It is a non-trivial task to match segments of the incoming speech signal to word forms and their meanings, let alone to determine the meaning of the whole when the words are combined into a sentence. The task of the sentence processor involves integrating the linguistic input (words) that bear one (or even multiple) meaning(s) with the structure that dictates how the input should be accommodated for mental computations. Several steps and processes, informed by everything from linguistic knowledge and mental representations to world knowledge, must take place before we reach the level of *understanding*. Take for example the following sentences:

(1) a. Stavroula kissed Emilios

b. Stavroula was kissed by Emilios

In (1a) *Stavroula* and *Emilios* (being proper names) each denote animate entities that are female and male, respectively, and *kiss* (being a verb) denotes an action between two, usually animate, entities. The fact that *Stavroula* is mentioned before *Emilios* doesn't instantly make her the agent of the kissing, even in languages like English, that do not overtly mark case. This is apparent from passive sentences like (1b), where although the serial position of the proper names is the same as in (1a), in (1b) it is *Stavroula* undergoing the kissing. Who is the agent and who the receiver of the kissing are expressed by the *structure* of the sentence. Structure is a fundamental component of language processing. But not the only one.

For structure to be applied, the processor requires mental representations of the lexical items. The *mental lexicon*, the repository of our lexical linguistic knowledge, resides in memory, and more precisely in long-term memory (LTM), and contains encoded lexical items. Their encoding (what I will refer to as a *chunk*) includes information about the phonological encoding of the words and their *features*, like gender, case, number (for nouns, adjectives) or person, number, tense etc. (for verbs), as well as information about their meaning. The language computational system, the *parser*, accesses memory to activate or retrieve the chunks and uses the features to apply the structure and build a sentence. But, *how do we understand?*

We understand the sentence when we *interpret* the sentence and the interpretation of a sentence might be influenced also by factors outside grammar. Each lexical item or linguistic expression (for example a noun, a verb, a proper name etc.) denotes something (an object, an action, an entity etc.) according to its characteristics. But language alone cannot tell whether (2a) is a true sentence.

(2) a. Maxima is the Queen of the Netherlands

b. Maxima likes the Queen of the Netherlands

c. Maxima likes herself

d. Stavroula knows that Maxima likes her

Language also cannot tell whether (2b) and (2c) *mean* the same thing. It is structure that informs us about the fact that in (2a) the female entity denoted by *Maxima* is in a predicative relationship with the female entity denoted by *the Queen of the Netherlands*. If you have some connection to the Netherlands or a particular interest in royal families, you should know by now that the Queen of the Netherlands is Maxima and you can therefore judge (2a) as a true sentence. This ability to judge truth value is the result of an extra-linguistic process. It is the result of identification of the two entities denoted by *Maxima* and *the Queen of the Netherlands*, using information about the relationship that the entities referred to by the linguistic expressions have in the world (in this case, an identity relationship). The same holds for (2b), in which, the proper name *Maxima* is in a "liking" relationship with the nominal phrase *the Queen of the Netherlands*. But whether this sentence means the same as (2c) is a matter of world knowledge. It is not a matter of language.

Having said that, think about the reflexive pronoun *herself*. In (2c) we understand the pronoun *herself* to refer to *Maxima* because the grammatical properties of the pronoun *herself* tell the language processor that it cannot be interpreted unless it gets connected to another expression (that denotes, in this case, a female entity) *within* the sentence. Grammar hence must create a dependency between *herself* and *Maxima* to enable interpretation of the pronoun through the entity that *Maxima* denotes.[1] Anaphors, in general, are thought to be underspecified in the sense that they are unable to get an *interpretation* by themselves. They need grammar to connect them to an expression from which they can take a reference and get interpreted. What needs to be clear is that the identification of the referents of the two arguments of (2c), *Maxima*

[1] A more detailed description of the properties and constraints of pronouns is given in Section 4.1

and *herself* is a result of a grammatical process. But the fact that (2c) and (2b) express the same thing is a result of our *world knowledge* that identifies the entities involved in (2b) as referring to the same individual.

Now take *her* in (2d) for which structure says that it is the patient of "Maxima's liking" but structure *alone* doesn't really help for its interpretation . The pronoun *her* indicates something female and must be an entity, contrary to *herself*, *outside* of the clause, either in a structurally compatible position or in the context. *Her* can, thus, either refer to *Stavroula* or to some other female entity present in the (broader) discourse. Linguistic theory, along with our intuition, tells us that underspecified lexical items need to find referents in order to be interpreted. They do so either by building dependencies within - approximately - the minimal clause (like anaphors) or by co-valuation with a suitable antecedent outside this domain (like pronouns). What is important to keep in mind is that, in any case, there is a "search-to-find" process taking place among possible candidate entities, that involves memory. Hence memory is not only crucial for lexical access but also for processing and interpretation.

In a nutshell, lexical knowledge, structure, memory, and world knowledge are the key ingredients of language comprehension. Indeed, the speed with which we can combine and compute information from all the sources, given that we are able to participate in normal-paced conversations, is puzzling and surprising. I will mainly deal with the stage of sentence processing that comes *before* interpretation, namely with the processes involved from lexical access to the formation of interpret*able* constituents.

1.2 Economy and processing cost

Sentence processing refers to the flow of computations that serve sentence comprehension and has a temporal component, in the sense that processing evolves in subsequent steps in time. When we try to figure out how exactly it proceeds and how much time it will take to process a sentence, we need to describe both structural (syntax) and cognitive (memory) properties. Linguists explore the language processing system by testing elements of linguistic theory in controlled experiments and they obtain measurements such as reading times, eye gaze, and various others, depending on the method used, which are indicative of the effort that the cognitive system dedicates to each task and computation step. The term *processing cost* has been widely used in the literature to express that effort and, conventionally, if something is easy to process then it is considered to be computationally "cheap".

What makes something "cheap"?

It is often the case that some sentences often seem harder to understand than others. It is not always the case, as one might easily think, that this results from how rare or difficult words can be in terms of their meaning. For example, (3a) is not *structurally* more difficult to process than (3b).

(3) a. Anna has agoraphobia
    b. Anna has fever

There is nothing more complex in *agoraphobia* in comparison to *fever* except for the fact that an English-speaking person might not know the meaning of the word (in contrast to a Greek speaker, as *agoraphobia* has a Greek origin). In that case, it might take longer to understand (3a) but this does not constitute a problem of complexity. It is rather a result of competence and knowledge (we cannot say that it is hard to ride a "gike" if we don't know what a "gike" is). Complexity is modulated by structure and memory *limitations* (the key ingredients to sentence comprehension).

Difficulty also arises when a word is ambiguous, as we can see in simple cases, like *the bank* in (4), or in more complicated cases, like the one in (5). To quantify processing complexity, hence, it is necessary to make a distinction between the sentence's structural complexity and the cognitive demands of the sentence's lexical elements.

(4) Anna passed by the bank (*lexical ambiguity*)

(5) A Ship shipping ship shipping shipping ships (*lexical ambiguity*)

(6) Anna saw the man with the binoculars (*structural ambiguity*)

(7) The horse raced past the barn fell (*garden path*)

The example in (6) is a case of structural ambiguity as the phrase *with the binoculars* can either modify the object, *the man*, and be interpreted as "Anna saw the man that was using binoculars" or it can be an instrumental modifier of the verb and be interpreted as "Anna saw the man while she was using the binoculars".

The processing demands of (6) are higher than that of cases like in (3), in the sense that one needs context to figure out the correct interpretation, a process that might add on processing time. Case (7) is an extreme case of a reduced relative clause and listeners find it often troublesome to understand because they first tend to interpret *raced* as the matrix verb of the clause, a choice that needs to be re-analysed as soon as *fell* is encountered (Mac Donald et al., 1992; Waters and Caplan, 1996). Its alternative, "The horse that was raced past the barn fell" is a lot easier because there is no misinterpretation of the lemma *raced* and thence no need for reanalysis. Case (5) exemplifies cases where the difficulty stems from the ambiguity of a word. *Ship* can be used either as a verb or as a noun making it tricky to distinguish its intended use in real time. Although the sentence is eventually understood as "A Ships that can ship ships, is [indeed] shipping ships that can ship ships", it clearly takes a longer time to figure out what ships what as a result of this ambiguity of the lexical entry [*ship*].

To sum up, language understanding is generally effortless, but it can become effortful when the linguistic constraints require processes that challenge and exceed the cognitive system's processing resources. It does not come as a surprise that there is no consensus yet on how we can know, a priori, which sentences are complex for the human processing system. Quantifying complexity is complex.

1.3 The puzzle

Quantifying complexity might be complex, but certainly not unattainable. You just need to start somewhere. The big question is: *What makes a sentence difficult to process*? On the one hand there is memory, a part of our cognitive system that can learn, store, retrieve and embellish our knowledge. And on the other hand there is language, that needs to be learned, uses storage, and requires retrievals and embellishing. Both systems seem to go along, communicate and collaborate right from the start even if sometimes the one must take priority over the other. The puzzle is how. Or,

How is the interplay between the properties of memory and the linguistic constraints mirrored in the speed of sentence processing?

Based on a model of sentence processing (Chapter 2), I zoom in on the organization of the lexicon and on lexical access. I quantify the speed of lexical activation by looking at the way that lexical items are stored. Making use of the tools that Information Theory provides I quantify one of the factors that modulate the speed of activation, namely the number of neighbours and the nature of the connections of the paradigm in the storage of LTM (Chapter 3). I narrow the study down to verbs and focus on the verb's closest network, the inflectional paradigm.[2]

With a constant and very low structural complexity I show experimentally how the first activation of lexical items, and thus the consumed processing resources, affects the speed of sentence processing. (Chapter 4 & 5). I look at small children as well, to approach the issue developmentally and get an insight into the time course of the computational

[2]I start from the inflectional paradigm of a verb but I believe that the same rationale can, and should, be used to estimate the influence of larger networks, such as the semantic one.

system's development (Chapter 6). In Chapter 7 we will see to what extent this approach explains the speed of processing, bit by bit.

CHAPTER 2

Memory and sentence processing

A promising approach to the understanding of memory systems is Ullman's Declarative/Procedural model (D/P model, (Ullman, 2004)), who draws on neuropsychological work on memory by (e.g. Cohen and Squire, 1980; Damasio and Damasio, 1992; Squire et al., 1993), and applies it language. The D/P model distinguishes two major domains within the memory system, the declarative and the procedural memory, which are mostly, structurally and functionally, independent. The declarative memory system is responsible for the learning and representation of knowledge about *facts* or personally experienced *events* such as knowing that water boils at 100 degrees Celsius or that strong lights give you a headache. It is specialized for handling the association of multiple pieces of arbitrary related information. Its learning is quick and (partially) explicit in the sense that it is consciously accessible to multiple mental systems, and highly flexible (Ullman, 2007). The procedural memory system is related to the learning of new, and controlling of already established, sensori-motor and cognitive skills (such as riding a bicycle) and its learning is gradual, based on a trigger-response mechanism, implicit, and no conscious access is possible. With respect to language, the D/P model suggests that the mental-lexicon component is part of the declarative domain and the mental-grammar component in the procedural one. Sentences are created when lexical items trigger grammar (Ullman, 2004). The computational system, the parser, dictates how the lexicon will interact with grammar and, in fact, there are several ways this can be done.

2.1 Technicalities of sentence processing

A good parsing model must be cognitively plausible. It must mirror, as accurately as possible, human performance during sentence processing, even if that means that it will be computationally less efficient. It needs to be able to capture *incrementality*, that is, the fact that sentences are processed word-by-word although the meaning does not necessarily emerge in such a sequence. It must also be able to identify and deal with *ambiguities*, either lexical or syntactic, and predict *complexity* in the expected positions, as they are highlighted by the experimental data. A parsing model consists of an algorithm that guides the way that the lexical items will be treated and of a set of other constraints and properties that guide its processing. The majority of existing approaches use one of three algorithms, which are presented in Section (2.1.1); this is followed by a presentation of some proposed parsing models that range from strictly "grammar-centred" ones, in which constraints are imposed by grammar only, up to "grammar-blind" ones in which constraints are ruled only by statistics.

2.1.1 Parsing algorithms

Parsers are classified in three main categories based on the algorithms they use to combine lexical items and grammatical rules: bottom-up, top-down and left-corner algorithms (see (Crocker, 1999) for an overview).

The bottom-up algorithms make use of a *stack* that keeps track of categories already found, along with one *shift* and one *reduce* operation that guide integration of new incoming words. Words are left in the stack and put together after a possible constituent can be completed, which causes a psychologically implausible delay and fails to capture incrementality (see (Stabler, 1994) for discussion).

The top-down algorithms also assume a stack, which however keeps track of the categories *to be found*. Essentially, in top-down algorithms, there is a complete structure, a sentence S, created from the very first word. Because the structure is not guided by the incoming material, it will fail in cases that the input does not fit into the assumed connected tree and the reanalysis needed will be costly and cause delay (recall the garden path example in (7)).

The left-corner (L-C) algorithm assumes a sentence S (as in top-down), builds categories as driven by the input (as in bottom-up) and *predicts* the next categories as dictated by the primary structure S and the incoming words. It combines the advantages of the two other alternatives, namely it is both incremental and data driven and does not, in accordance to the empirical data, exhibit unnatural delays (e.g. due to the interpretation after completion requirement of bottom-up algorithms) or unnecessary reanalysis (e.g. a drawback of top-down algorithms). The L-C algorithm is generally considered the, biologically, most plausible and closest description of how the human parser might work.

2.1.2 Parsing models

When we complete a task in real time, from participating in a conversation to calculating the change from the grocery store, we need to keep representations active and crucially, more active than all the knowledge that we have. For example, if we need to make sure that the 2 euro we got back from our 10 euro bill we gave for groceries of 8 euro value (a task that simple!) is the correct amount of change, we essentially need to perform the subtraction of $10 - 8$, which requires keeping 10, 8 and the process "$-$" more active than, say, the rest of the numbers we know.

That is how the notion of Working Memory (WM), as distinct from Long Term Memory, emerged. Although Ullman's model (Section 2) does not describe how online processing in WM functions, the issue of the architecture and the interplay of WM and LTM has been and widely studied and debated. A main feature that distinguishes the different views on memory is whether WM is architecturally distinct from LTM, forming two main streams of *multi-store* (e.g. Baddeley and Hitch, 1974; Baddeley, 1992, 2003) versus *unitary-stored* (e.g. McElree, 2006; Cowan, 2001) models of WM.

The models for language parsing can be classified by the ways that they deal with complexity, or, in other words, on how the imposed constraints interact with each other to lead to some sentences being more complex than others. A tricky part here is that some times what is computationally more efficient for the algorithm can be behaviourally less preferred by humans. For example, take (6), an example of a structurally ambiguous sentence (repeated below as (8)).

(8) Anna saw the man with the binoculars

As before, (8) can be ambiguous in the sense that the phrase *with the binoculars* can either modify the DP *the man* (*low* attachment, Figure 2.1), or the VP *saw* (*high* attachment, Figure 2.2). From the trees in Figures 2.1 and 2.2, one can see that the first case, where the modifier is attached *low*, seems more complex (since the tree has more nodes) than the second one, where the modifier is attached *high*. However, evidence regarding the preference of the human processor seems to be dependent on the experimental task and the experimental items used: there exists experimental evidence that people prefer high over low attachment (e.g. Ferreira and Clifton, 1986) but also other evidence showing a preference (that depends on the context) for low over high attachment (e.g. MacDonald et al., 1994; Trueswell et al., 1994). As mentioned before, a good parser should be able to relate computational efficiency to the observed human measures. Consequently, another distinction emerges that is based on whether the constraints of initial structure building are mainly imposed by grammar/structure (Frazier, 1979; Pritchett, 1992) or if they allow other factors, such as memory limitations or frequency of use, to come into play (Gibson, 2000; MacDonald, 1994; Hale, 2001).

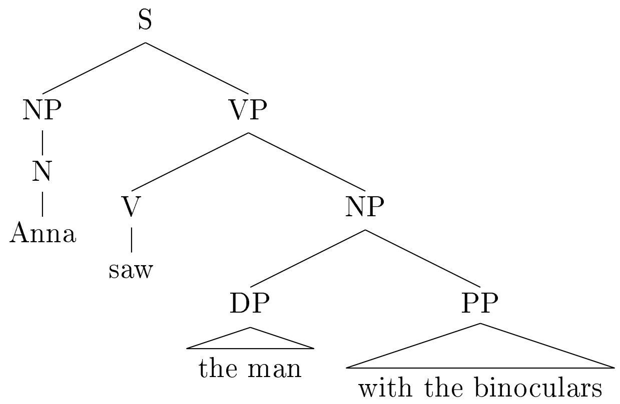


Figure 2.1: *low attachment* Anna saw the man that was using binoculars

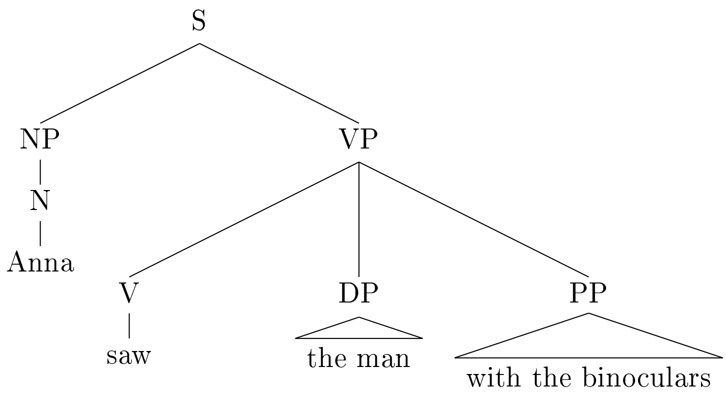


Figure 2.2: *high attachment* Anna used saw the man while using the binoculars

Early studies in sentence processing gave rise to models that considered structural or grammatical constraints to be the main guide on how each word is attached to the structure.

A structural based parser like the "Garden Path Theory" (Frazier and Fodor, 1978) assumes that the parser can build only one syntactic structure at a time that and that it always chooses the least complicated possibility. Such a parser integrates each word under the guidance of two principles: *minimal attachment* (MA) and *late closure* (LC). LC allows attachment of each new word into the current partial structure (clause) as long as it is plausible and MA prevents redundant nodes from being constructed. Thus, in cases of structurally ambiguous sentences like (8), the structure that introduces fewer nodes would be considered more economical. In temporal ambiguities, in cases where the chosen structure does not fit the subsequent incoming words, reanalysis is needed, which leads to harder processing and longer processing times.

The grammar-based parser of Pritchett (Pritchett, 1992) makes use only of head-based information (it is thus called a “head-driven” parser). The main principle of the parser is “Theta Attachment”, which seeks to maximally satisfy, at each point, the “Theta-Criterion” of the head. To put it simply, each incoming word is immediately attached to the head’s open syntactic positions (like agent-theme). In Pritchett’s parser reanalysis is expected and it is not costly, unless not done automatically.

The above-mentioned parsing models do not take into account memory limitations, which are, as discussed, a fundamental factor in human parsing. More recent models have included memory and frequency and/or expectation constraints. Some of them are completely blind to structural constraints, while others use a combination of both structural and “usage-based” constraints. Below, only some will be briefly described to explain their main ideas and differences.

An experience-based parsing model (MacDonald, 1994) is sensitive only to the statistical information that emerge from the frequency of particular lexical items or structures. Lexical integration therefore depends only on how “expected” the new word is, in terms of its frequency of use *in general*, totally ignoring structural constraints. Unexpected words that are to be fitted in the incomplete structure (e.g. a verb instead of a noun) result in reanalysis.

Memory-based accounts, like the “Dependency Locality Theory” (Gibson, 1998, 2000; Grodner and Gibson, 2005) assume only one statistical parameter that determines which structure is preferred (when the sentences is ambiguous) and posit that processing complexity results from memory constraints. Difficulty in processing emerges when the limited capacity of WM is exhausted. Cost is measured by the number of "open" dependencies of constituents at each processing step, or else, by the number of heads encountered at the processing step under study. The more incomplete constituents, the higher the cost. Such a model would give the same prediction of processing difficulty for example to both instances of the ambiguity in (8) in terms of integration cost, but would correctly predict human behaviour with the use of its statistical component. The higher frequency of low attachment would give the preferred interpretation an advantage in processing times contrary to less frequent high attachment (Taraban and McClelland, 1988).

Expectation based models (Levy, 2008; Hale, 2001) rely on the intuition that the way humans *expect* a sentence to continue can significantly influence their processing speed. Based on experiments that demonstrate the high extent to which listeners use context to predict the continuation of a sentence (Marslen-Wilson, 1975) and that correct expectations increase the processing speed of new input, these models suggest that structural and lexical expectations must be combined in order to explain sentence comprehension.

Interference-based models (Lewis and Vasishth, 2005; van Dyke and McElree, 2006) are also based on the idea that the parser is sensitive to structure and memory constraints, but they assume the difficulty to result from an interference induced by the existence of similar items in memory during the retrieval process. A detailed example of this model will be presented in the following section (2.3) as it is the one that, in my view, closely explains all the cognitive and behavioural evidence. Before moving on to the description of Lewis & Vasishth's (henceforth L&V) model, I will briefly address another issue that deals with the structural nature of LTM and WM.

2.2 Is WM distinct from LTM?

Baddeley (Baddeley and Hitch, 1974; Baddeley, 1992, 2003) presented an influential model that describes WM as a functionally distinct system from LTM that is divided into distinct buffers: the phonological, the visuo-spatial and the episodic. The way that these buffers interact is managed by a collection of processes, named the "central executive".

On the other hand, pursuers of the unitary store models suggest that WM and LTM have essentially the same architecture (and a great functional overlap) and the stored items have representations of varying activation. According to those models, WM is an instantiation of LTM, consisting of the elements that have, temporarily, higher activation. The elements immediately available for processing are in the so-called "Focus of attention" (FoA) (McElree, 2001). The bandwidth of the FoA is thought to be extremely limited although the exact number is not identically assumed in all relevant models (it can range from one to four items) (McElree, 2006; Cowan, 2001).

Evidence for the functional distinction between WM and LTM comes from neurophysiological studies and patients that have damage in the parietal temporal lobe (PTL) and have impaired performance in tasks requiring WM, while their LTM is intact (Shallice and Warrington, 1970; Vallar and Papagno, 1995), and those with a lesion in the medial temporal lobe (MTL) that have poor performance in tasks targeting LTM and a healthy-like performance in tasks targeting STM (Scoville and Milner, 1957; Baddeley and Warrington, 1970). The dual dissociation lead Baddeley (among others) to suggest that WM is supported by the PTL while LTM is supported by the MTL. However, meta-analyses of the mentioned studies (Cabeza and Nyberg, 2000; Cabeza et al., 2002) questioned whether the WM tasks targeted only WM and not LTM as well. MTL has been shown to be critical for the declarative memory, in LTM (Squire, 1992; Gabrieli et al., 1997), but has also been shown to correlate with WM tasks leading researchers to propose that MTL is critical for the establishing and binding of novel representations. This claim has been supported by studies with amnesic patients, with a lesion in the MTL, that usually do not show any WM irregularities, unless they are faced with representing, or binding, novel material (Hannula et al., 2006; Olson et al., 2006).[1]

When it comes to the different storage buffers in WM, at a first glance, the unitary store accounts seem to deny the need for this specification. At a closer look though, the assumption is common in both views; there has to be a distinction in the sources of information, in the sense that e.g. spatial-related stimuli shall be processed (even slightly) different than verbal ones.

L&V (Lewis and Vasishth, 2005) focused on language processing and used a model from cognitive psychology to develop a model for sentence processing that is, in my view, the most psychologically plausible, as it provides simulations that are consistent with the empirical evidence. It is an interference, cue-based model that considers structural *and* memory limitations to describe the processes and costs involved in sentence processing. Based on the cognitive principles of an association-based model of memory, the Adaptive Control of Thought-Rational (ACT-R) architecture (Anderson and Lebiere, 1998; Anderson et al., 2004; Anderson, 2005b), and in line with the general principles of the Ullman's D/P memory model, L&V provide a model of sentence processing, adapted to linguistic considerations, that gives a detailed account of the function of working memory in sentence comprehension. The model starts out from local ambiguities being the main problem of WM, as was the case for a lot of enlightening and pioneering approaches (Altmann and Steedman, 1988; Frazier and Rayner, 1982; Ferreira and Clifton, 1986, among others), and focuses on the pure need of any model to have a way to temporarily keep recently completed material active for reference and

[1]For a comprehensive overview and an extensive discussion of the evidence in relation to the functional and neurophysiological distinction of Short-term, Long-term and Working memory see Jonides et al. (2008) and references therein.

retrieval as well as incomplete constituents ready to integrate incoming lexical items.

2.3 A model of working memory for sentence comprehension

The model proposed by L&V (Lewis and Vasishth, 2005; Lewis et al., 2006) describes all stages of sentence processing, from lexical access to successful interpretation, but it gives a full description mainly of the function of working memory and the syntactic parser, leaving the part of lexical access open for further investigation. The model follows the principles of unitary storage accounts, assuming an LTM with stored items with representations of fluctuating activation, which are brought to the focus of attention (FoA) for immediate binding. Recently activated items have a higher activation level than those items in LTM because they have just been retrieved, and for the sake of simplicity, I will refer to those as being stored in WM.

In particular, a sentence is processed by an interplay between the newly encountered lexical items that activate grammatical rules (called "production" rules in the original paper), which, in turn, through a *search* operation (context-based cue), retrieve representations from the lexicon and the already-parsed structure while, at the same time, creating cues for the structure predicted. WM manages the cues and the representations of the "to-be-integrated" lexical item (the target) and keeps track of the "to-be-expected" structure (the goal). Retrieval from WM through the context-based cues is subject to interference from stored items with *similar* representations. WM consists of the *Focus of Attention* (FoA) and three one-chunk *buffers* that, at each parsing point, store a representation of the result of lexical access (lexical buffer), the constituent just retrieved from WM (retrieval buffer) and a local control state that includes the syntactic goal-category (control buffer).

The Focus of Attention, in contrast to traditional views like Miller's proposal that WM has a span of ± 7 as measured by the classical measure of serial recall (Miller, 1994), has a very limited size of 2 chunks. This limited capacity might look too small but it is the one that is supported by a growing amount of empirical data from speed-accuracy trade-off (SAT) analyses that looked for the minimum capacity used by the human system to establish novel relations (McElree et al., 2003; McElree, 2006). Additionally, as indicated by the STA studies, fast retrieval is a result of a parallel match of cues against all items in memory and the serial position of the preceding items does not constitute valuable information for the search. There is no functional distinction between LTM and WM, assuming that they are both part of the declarative memory. Grammatical rules include structural information and act procedurally.

In more detail, retrieved lexical items are stored in declarative memory, and are represented as *chunks*, that is, a bundle of syntactic (tense, agreement etc.) and semantic features. Chunks can have connections to other chunks, forming networks, such as, the inflectional paradigm of a verb or other phonological or semantic networks. The goal of the search operation is to match a content-addressed cue stemming from the input lexical item (a subset of the item's bundle of features) with the chunks of the stored lexical items.

A target word retrieves its representation from LTM, which is then stored, as a maximal projection, with information about its X-bar position (the place in the syntactic structural tree) on the lexical buffer. At the same time two grammatical rules are triggered. One content-addressed cue (BackR) is formed by a subset of the features of the target word that contain structural information, and searches in the retrieval buffer for incomplete constituents that are good candidates for the integration of the target. The second rule (AttR) realizes the attachment of the target to the retrieved constituent (in the Focus of Attention).[2] In the case that the content-addressed cue finds more constituents as good

[2]The terms BackR and AttR are not used in L&V's terminology. I introduced them for simplicity of reference.

candidates, the “search-to-find process” is slowed down because of interference. Hence, at the point of an incoming word the following processes

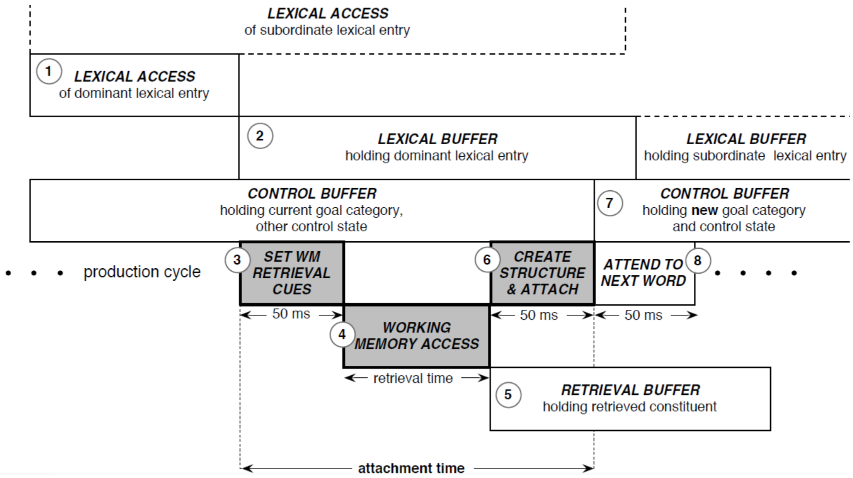


Figure 2.3: Overview of the model, showing the critical focus buffers (control buffer, lexical buffer, and retrieval buffer) and processing dynamics (time flows left to right). The three key working-memory processes are shown in gray: (3) a production rule (BackR) encoding grammatical knowledge sets cues for retrieval of a prior constituent; (4) a prior constituent is retrieved from working memory via parallel associative access; and (6) a second production rule (AttR) creates the new structure and attaches it to the retrieved constituent (taken from Lewis and Vasishth (2005), pg 383).

take place:

1. The new word (target) identifies and retrieves its representation (its chunk) in LTM.
2. The activated representation is in the Focus of Attention and expects the structure chunk to be retrieved from one of the WM buffers. There is a maximum of two chunks in FoA per processing step.
3. One grammatical rule (BackR) searches in the retrieval buffer to find a suitable incomplete constituent. (All “search-to-find” processes are subject to delay caused by interference in case of similar representations.)
4. BackR retrieves a suitable constituent and brings it to the FoA.

5. One grammatical rule (AttR) combines the two novel representations (the target word and the retrieved constituent).
6. The just-created constituent is stored in WM.
7. The Focus of Attention (FoA) now contains the new incoming word and the loop starts again.
8. In case that BackR retrieved a wrong constituent (as in cases of garden paths), reanalysis occurs through activation of neglected constituents in the memory.

The speed of processing in WM is described by functions following the basic ACT-R architecture. Each chunk i in WM has a level of *Total Activation* (A_i, Formula 9a) and of an associative amount of activation. The terms W_j, in Formula 9a, express weights associated with the goal chunk and each term S_{ij} describe the strength of association between chunk i and chunk j. Total Activation is a function of usage history and delay (as seen by the *base level of activation* B_i, Formula 9c) and is an index of retrieval latency and the probability of retrieval. Total Activation is mapped onto latency of retrieval through Formula 9d.

(9) Equations of ACT-R

a. Total activation: $A_i = B_i + \sum_j W_j S_{ji}$,

b. Associative retrieval interference: $S_{ji} = S - \ln(fan_j)$,
where S is the maximum associated strength and fan_j are the items associated with i in WM

c. Base level of activation: $B_i = ln(\sum_{j=1}^{n} t_j^{-d})$,
where d is the decay parameter, computationally estimated to be 0.15

d. Retrieval latency: $T_i = Fe^{-A_i}$,
where F is a scaling constant (in L&V's simulations this is set to be 0.14)

2.3.1 Example of a processed sentence

To exemplify how the parser of L&V's model works, consider sentence (10) below:

(10) The writer surprised the editor

- *The*: the lexical item is identified and retrieved from LTM (exact process not described in the model)
  D1= [cat: D, head: *the*]
  - BackR is set to retrieve the IP that is predicted by the Determiner input:
    IP1= [cat: IP, spec: DP1, comp: VP1]
  - AttR attaches *the* at the specifier position D of the DP1 inside the retrieved IP:
    IP1= [cat: IP, spec: DP1(*the*, comp: NP1), comp: VP1]
  - the incomplete IP1 is temporarily stored in WM, anticipating a VP
  - the incomplete DP1 is stored in focus of attention (FoA) anticipating an NP1:
    DP1= [cat: DP, head: *the*, comp: NP1]
- *writer*: the lexical item is identified and retrieved from LTM
  NP1= [cat:NP, head: *writer*, num: sing, case: nom]
  - BackR searches for an NP and immediately finds the NP1 inside the incomplete DP1 in FoA
  - AttR attaches the NP1 *writer* at the head of the incomplete DP1:
    (updated) DP1= [cat: DP, head: *the*, comp: NP1(cat:NP, head: *writer*, num: sing, case: nom)]
  - DP1 *the writer* is stored in FoA
- *surprised*: the lexical item is identified and retrieved from LTM
  V = [cat:V, head: *surprised*, num: sing-plural, tense: past]

- BackR searches for a VP and finds the VP1 in the incomplete IP1 which by now contains *the writer*:
  VP1= [cat: VP, head: V, comp: DP2]
- AttR attaches *surprised* at the head of the VP1:
  VP1= [cat: VP, num: sing-plural, tense: past, head: *surprised*, comp: DP2]
- the incomplete VP1 is stored in FoA and is expecting a DP2

• *the*: the lexical item is identified and retrieved from LTM
D2= [cat: D, head: *the*]

- Back R retrieves the DP2, as predicted by the Determiner, inside the VP1
- AttR attaches the as subject of the predicted DP2 under the VP1:
  (updated) VP1= [cat:VP, num: sing-plural, tense: past, head: *surprised*, comp: DP2(cat: DP, head: *the*, comp: NP2)]
- the incomplete DP2 structure is stored in focus of attention (FoA) expecting an NP2:
  DP2= [cat: DP, head: *the*, comp: NP2]

• *editor*: the lexical item is identified and NP2 is retrieved from LTM:
NP2=[cat:NP, head: *editor*, num: sing, case: acc]

- BackR searches for an incomplete DP and retrieves DP2
- AttR attaches *editor* to the head position of the incomplete DP2:
  (updated) DP2= [cat: DP, head: *the*, comp: NP2(cat: NP, head: *editor*, num: sing, case: acc)]

Once again, the processes that act in a loop concern lexical access, structure rules (what L&V call production rules), WM retrieval and attachment rules. As seen in the example, lexical access is assumed to take place but not explained in detail, a topic that will be the content of the next section.

2.3.2 Lexical access in the L&V framework

The L&V model describes in detail how chunks, already processed and in the FoA, are retrieved from WM, positing that speed of retrieval is influenced by the degree of similarity of candidate chunks, that is, the degree of feature overlap among the stored chunks. What the model, deliberately, does not discuss in detail is the possible similarity interference at the level of lexical access, although the authors acknowledge that the principle should be the same. They follow Gordon et al. (Gordon et al., 2004) and state that 'lexical access delays might be understood as *encoding* interference, [an analysis] that is missing from all current processing models' (Lewis and Vasishth, 2005, pg. 412). The authors leave the issue open for future investigation.

In ACT-R, lexical items are represented as chunks that can have connections to other chunks and are characterized by a base level of activation that is a function of the time between successive retrievals and decay rate. The formulas in (9) quantify the activation properties of items stored *in WM*. So, at each processing step of a sentence like (10) one can obtain, through Formula 9a, the amount of Total Activation in WM of [*The*], [*The writer*], [*The writer surprised*] etc. But "Total Activation" refers to the amount of activation that the just-activated element or constituent has, in WM, and is a function of its base level of activation, after retrieval, and the boost from the retrieval cues. In LTM a lexical item has no "Total Activation", in the sense of L&V and Formula 9a, because there is no boost from retrieval cues, as these are only triggered *after* the item is activated. ACT-R provides no Formula to quantify the speed of the *first* activation of the isolated lexical items *the*, *writer* or *surprised*.[3] The question that follows is:

Q1: What is the ease of access for the first time, of each individual

[3] Formula 9d gives an estimation of the speed of retrieval, which does not however depend on the properties of the activation of the item in LTM. It is rather calculated through A_i, which is a property of the item's activation when it is already stored in WM.

lexical item?

I see no need to postulate new kinds of processes that apply to LTM and lexical retrieval. I take lexical items stored in LTM to be influenced by the same factors as when temporarily stored in WM. Consequently, lexical items in LTM are also connected in networks and have a fluctuating activation, which I will call the *Activation Potential* (AP). An item's "Activation Potential" indicates its *accessibility*, or how "ready for activation it is", and is influenced (among other factors) by the neighbours in the network it belongs in (11).[4] All members of a lexical network are influenced (in a supportive or inhibitory manner) by their network and the similarity among its members. It is important to note that similarity is inhibitory only in the case that there is a "search-to-find" process among the members of the network. In all other cases similarity among the items of a network has a *facilitatory* effect. I will come back to that point in the next chapter.

(11) Activation Potential (AP) of a lexical item in LTM:
$AP_i = X +$ Network's Influence

Hence,

A1: The ease of access of a lexical item *for the first time* is proportional to the item's *Activation Potential.*

The next chapter will address the missing part of L&V's model (circled in Figure 2.3) and will provide a quantitative description of lexical access. The *Activation Potential* of stored lexical items will be approximated with the help of Information Theory (Shannon, 1948) and its tools adapted to describe language processing.

[4]I do not claim that the influence of the network is the *only* factor that determines AP, but it will be the one I will focus on. To what follows, I will mostly mention this without implying that the other factors are absent.

CHAPTER 3

Information Theory applied to language

3.1 Some words are read faster than others

Sentence comprehension is the result of the interaction between lexical items and structure. The linguistic signal points to a mental representation of the target word and projects structure. The ease of sentence processing depends on grammatical and cognitive constraints. The focus of this work is the study of the organization of the lexicon and its influence on online sentence comprehension. As seen in Section 2.3, processing in WM is sensitive to the similarity of the items that are activated at the same time. The ease of lexical access should also be sensitive to the same property. Lexical items are stored in LTM and are connected in networks. How can we estimate the similarity of the items in LTM? We could think that, e.g., synonyms are more similar than antonyms. But the lexicon is organized in a much more detailed way and it suffices to zoom in to see that even words that morpho-phonologically overlap might be very different in processing terms.

In work done on SerBoCroatian, a language that is highly inflected for case and number, it has been found that nouns were read faster when presented in the nominative case than in any other case (Lukatela et al., 1980).[1] Kostić noticed that this difference between inflected forms of the same noun could not be captured by theories concerning the lexicon, nor by the frequency of each inflected type alone. He claimed that the ease of processing an inflected noun is influenced by the "information" carried in its inflectional morphology. He calculated the "information" of each form using the formulas provided by Shannon's "Information Theory" (Shannon, 1948) and found that this measure is a better predictor for naming and reading latencies of words in isolation than other factors known to influence human processing, such as word length, frequency or phonological patterning (Kostić, 1991).

Similarly, the same happens with other languages and other lexical categories as it will be outlined in Section 3.4. Before discussing the studies that use an information theoretical approach to language processing, I will first introduce the basic intuitions and notions of Information Theory and how they are adapted to language. The quantification of the "Activation potential", a property that relates to a network's organisation and similarity, and hence can be addressed through Information Theory's tools, will follow along with its consequences for the speed of sentence processing.

3.2 Information Theory: the basics

Shannon introduced in 1948, in his book *A mathematical theory of communication*, the notion of *Entropy* (H) of a discrete random variable X (Formula 12) to describe the uncertainty associated with this variable

[1] I am using the term SerBoCroatian (suggested by Marko Simonović and Boban Arsenijević) to refer to the polycentric standard language (Kordić, 2010) used as the official language in Serbia, Croatia, Bosnia and Herzegovina and Montenegro under different official names. The traditional name Serbo-Croatian has been modified here to include the third most common name (Bosnian).

and its distribution (Shannon, 1948). Shannon's work focused on signal processing and on how a message can be encoded in a way that can be transmitted through a "noisy" channel with the least loss possible. Shannon's entropy expresses the average number of bits that are needed to store a message.[2] In the years since, though, this theory and notion has been used in various domains such as, among others, cryptography, neurobiology, statistical inference, and as we will see later, in human language processing as well.

(12) Entropy of a random variable X:
$$H(X) = -\sum_{x \in X} p(x) \log p(x)$$

In order to simply explain the sense of H, I will shift from a discrete random variable to a discrete set consisting of c items. This set can be seen as a collection of any type of discrete elements with shared characteristics, e.g. a collection of books, of integers, of dresses in a cupboard or of words. We will refer to the actions that can be applied to this set as a "message" (in information-theoretical terms) that can be e.g., "a choice of a book", "let the second integer be even". The realization of these "messages" is estimated by their probability p. This "shift" from a discrete *variable* to discrete *items of a set* gives rise to Formulas 13a and 13b (Baayen et al., 2006).

(13) Shannon's formulas adapted to a set of discrete items

a. Information carried by an item i, measured in bits:
$IL_i = -\log_2 p_i$, where p_i denotes the probability of i, related to an event m

b. Entropy of a set f with c items, measured in bits:
$$H_{f_c} = -\sum_{i=1}^{c} p_i \times \log_2 p_i$$

To clarify how the formulas work, let us take a set to be f = "collection of c books" and an event m = "choose one book out of the set f. If

[2] A *bit* is the basic unit of information.

the collection consists of only one book ($c = 1$), then the probability to choose the only book b will be $p_b = 1$. Since there is no uncertainty about the choice of a book in a singleton set, the entropy will, unsurprisingly, be $H_{f_1} = -(1 \times \log_2 1) = 0$ bits and the information carried by the choice of the book will be $I_b = -\log_2 1 = 0$ bits.

In the case that $c = 8$ and the books are identical they will have the same probability of being chosen $p_b = \frac{1}{c} = \frac{1}{8}$. Consequently, the set f = "collection of 8 identical books", and the information carried by each "book-choice" is $I_b = -\log_2 \frac{1}{8} = 3$ bits. The entropy of set f is also $H_{f_8} = -(8 \times \frac{1}{8} \times \log_2 \frac{1}{8}) = 3$ bits. Notice that when the items of the set have the same probability then the entropy reaches its maximum value and $I \equiv H$.

However, it is not always the case that a set consists of items with the same probability. In fact, most of the time this situation does not occur in the real world. Let us take again a set of 8 books that have *different* probabilities of being chosen (because, for example, some are more interesting or bigger than others). Let $p_1 = p_2 = p_3 = p_4 = \frac{1}{8}$, $p_5 = p_6 = \frac{1}{16}$ and $p_7 = p_8 = \frac{3}{16}$. It follows that the individual information that each book carries is: $I_1 = I_2 = I_3 = I_4 = -\log_2 \frac{1}{8} = 3$ bits, $I_5 = I_6 = -\log_2 \frac{1}{16} = 4$ bits and $I_7 = I_8 = -\log_2 \frac{3}{16} = 2.415$ bits. It is easy to notice that the lower the probability of an item gets, the higher is the information that this item carries.The entropy of that set of books will be 2.906 bits according to the following calculation:

$$
\begin{aligned}
H'_{f_8} &= -\sum_{m=1}^{8} p_i \times \log_2 p_i \\
&= -\sum_{1}^{4} \frac{1}{8} \times \log_2 \frac{1}{8} - \sum_{5}^{6} \frac{1}{16} \times \log_2 \frac{1}{16} - \sum_{7}^{8} \frac{3}{16} \times \log_2 \frac{3}{16} \\
&= 4 \times \frac{1}{8} \times 3 + 2 \times \frac{1}{16} \times 4 + 2 \times \frac{3}{16} \times 2.415 = 2.906
\end{aligned}
$$

Thus, the Information entropy *changes* when the probabilities within the set *vary* and it is a measure of the uncertainty in predicting the outcome of a message.

One should be careful about the use of the term *information*. The technical notion of information, as a measure of uncertainty, is often confused with the intuitive notion of information that implies something clear and informative. The technical notion of information, as stressed even by Shannon himself, is a measure of how *unclear* something is and, in this sense, it is not surprising that buying a winning lottery ticket is a more informative event (as there is less certainty about which one is the winning one) than flipping a coin and getting a tail (50% chance). The Formulas in 13 measure the value of the technical notion.

3.3 Application of Information Theory to language

Coming back to language processing and to the observations stated in the beginning of this chapter, Kostić explained the results in the processing of the inflected SerBoCroatian nouns with the use of Information Theory (Kostić, 1991, 1995, 2013). He claimed that the uncertainty of the morpho-syntactic specification of a certain lexical form increases its information load (IL) and that increase results in the attested delays.

How can we map Shannon's formulas to language? We need to define a set and a distribution of probabilities for this set. For a word, the "closest" set that exists is the word's inflectional paradigm. A paradigm is a network consisting of all the words related to a lexeme. The inflectional paradigm of a word (the conjugation) consists of the stem, the basic unit of the word, and its inflected forms. Table 3.1 gives an example of an inflectional paradigm of the verb *helpen* ('to help', in Dutch).

The probability of each inflected form is, following Kostić, a function of the ratio of the relative frequency f of each verb form to the syntactic functions/meanings R each verb form can have, so Formula 13a becomes 14, and estimates the Information Load (IL) of each inflected verb form. The term *syntactic meanings/functions* was introduced to capture the fact that an inflected type can be used in syntactically different positions, as for example the verb type "work" in English, which can be used at the same time as 1^{st} & 2^{nd} person singular, but also for all persons in plural (and thus $R_{work} = 5$).

As for the Inflectional entropy of the paradigm, Moscoso del Prado Martín (2004, and following work) does not make use of the syntactic functions/meanings parameter R but rather adapts Formula 12 as in 15a, where F_P is the base frequency of the inflectional paradigm and F_i the surface frequency of the word. I will follow Kostić (and van Ewijk, 2013) and use Formula 15b that incorporates frequency of use and linguistic considerations as included by the term R.

(14) Information Load of an inflected verb form i:

$$IL_i = -\log_2 \frac{\frac{F_i}{R_i}}{\sum_{j=1}^{c} \frac{F_j}{R_j}}$$

(15) a. Inflectional entropy of a paradigm without the term for number of functions/meanings (R):

$$H_P = -\sum_{i \in P} \frac{F_i}{F_P} \times \log_2 \frac{F_i}{F_P}$$

b. Inflectional entropy of a paradigm with the term for number of functions/meanings (R):

$$H_p = -\sum_{i=1}^{c} \frac{\frac{F_i}{R_i}}{\sum_{j=1}^{c} \frac{F_j}{R_j}} \times \log_2 \frac{\frac{F_i}{R_i}}{\sum_{j=1}^{c} \frac{F_j}{R_j}},$$

Frequencies of the inflected forms are obtained from large corpora of written or spoken speech for the language under study. The variable

Table 3.1: Inflectional Paradigm of *helpen* ('to help', in Dutch). The verb forms that constitute the c members of the paradigm are marked in bold.

	1^{st},2^{nd} sg	ik,jij (interrogative)	**help**
Present	2^{nd}, 3^{rd} sg	jij, hij/zij/het, u	**helpt**
	1^{st},2^{nd},3^{rd} pl	wij, jullie, zij	**helpen**
Past	1^{st},2^{nd},3^{rd} sg	ik, jij, hij/zij/het, u	**hielp**
	1^{st},2^{nd},3^{rd} pl	wij, jullie, zij	**hielpen**
	1^{st}	ik heb	
	2^{nd}	jij hebt	
Perfect	2^{nd}, 3^{rd} sg	hij/zij/het, u heeft	**geholpen**
	1^{st},2^{nd},3^{rd} pl	wij, jullie, zij hebben	
Future	1^{st},2^{nd},3^{rd} sg	ik, jij, hij/zij/het, u zal	helpen
	1^{st},2^{nd},3^{rd} pl	wij, jullie, zij zullen	
Future Perfect	1^{st},2^{nd},3^{rd} sg	ik, jij, hij/zij/het,u zal hebben	geholpen
	1^{st},2^{nd},3^{rd} pl	wij, jullie, zij zullen hebben	
Infinitive			helpen
Participle			geholpen

(R) is the number of "syntactic functions/meanings" each verb form can serve. If a certain verb form w_1 (a particular morphological composition, an inflected type) can be used as an infinitive, and 1^{st}, 2^{nd} & 3^{rd} person plural, it follows that $R_{w_1} = 4$. This form will have a higher uncertainty (thus a higher information load) resulting in a "heavier", and costlier, type than a form w_2, with $R_{w_2} = 2$ that can only be used as an infinitive and a 1^{st} person singular (provided of course that these two forms have equal frequencies).[3]

Numerically, if w_1 and w_2 have a probability $p_1 = p_2 = 0.4$ and $R_{w_1} > R_{w_2}$, then $w1 = 3.322 > w2 = 2.322$ making w_2 harder to process. More functions create more ambiguity regarding the suitable environment a verb type can be used in, corresponding to higher load and cost correlated to the individual form's processing.

Clearly, the Information load of an inflected verb form and the Inflectional entropy of the verbal paradigm are language-dependent measures and because the present study investigates the effects of Inflectional entropy in Dutch and in Greek, I will exemplify the calculations of IL and InflH for the verbs *helpen* and *prijzen* ('to help' and 'to praise', respectively), in Dutch.[4]

From Table 3.1, six forms ($c = 6$) are identified; *help*, *helpt*, *hielp*, *hielpen*, *geholpen* and *helpen*. Relative frequencies were obtained from the CELEX lexical database (Baayen et al., 1995). For each verb type the number of syntactic functions (R) was identified and the ratios of relative frequencies to functions were calculated (F/R). To get a distribution of the probabilities of the paradigm the ratio was normalized, which resulted in a probability value p for each verb form. ILs for each form and the InflH of the paradigm is calculated with formulas 14 and 15b. Table 3.2 gives an example of the calculation of IL and InflH.

The Inflectional entropy of the verbal paradigm of *helpen* is 2.183

[3] Aspect (perfective) is taken to be encoded in the auxiliary verb and thus does *not* constitute a new syntactic environment.

[4] For corresponding examples in Greek, see Appendix A.

Table 3.2: Calculation of Information load and Inflectional entropy for the verb *helpen* ('to help', in Dutch)

$c = 6$	help	helpt	helpen	hielp	hielpen	geholpen
F	583	1420	6336	1533	302	1496
R	2	2	4	3	3	1
$\frac{F_i}{R_i}$	291.5	710	1584	511	100.7	1496
$p_i = \frac{\frac{F_i}{R_i}}{\sum_{j=1}^{6} \frac{F_j}{R_j}}$	.062	.151	.338	.109	.021	.319
$I_i = -\log_2 p_i$	4.009	2.725	1.567	3.199	5.543	1.65
$h_i = -p_i \log_2 p_i$	.25	.41	.53	.35	.119	.526
				$InflH =$	$-\sum_{j=1}^{6} p_j \log_2 p_j$	$= 2.183$

Table 3.3: Calculation of information load and Inflectional entropy for the verb *prijzen* ('to praise', in Dutch)

$c = 6$	prijs	prijst	prijzen	prees	prezen	geprezen
F	3230	88	1458	219	48	295
R	2	2	4	3	3	1
$\frac{F_i}{R_i}$	1615	44	364,5	73	16	295
$p_i = \frac{\frac{F_i}{R_i}}{\sum_{j=1}^{6} \frac{F_j}{R_j}}$	.671	.018	.151	.030	.007	.123
$I_i = -\log_2 p_i$	.576	5.774	2.724	5.043	7.233	3.029
$h_i = -p_i \log_2 p_i$	.386	.106	.412	.153	.048	.371
				$InflH =$	$-\sum_{j=1}^{6} p_j \log_2 p_j$	$= 1.476$

bits. It is a high value when compared to 1.476 bits (Table 3.3), which is the value of InflH for the paradigm of *prijzen* ('to praise', in Dutch). What does this mean?

The value of Inflectional entropy is a description of how the network is organized in the lexicon, how "uniform" the distribution of probabilities of the inflected forms within the paradigm is. Low Inflectional entropy indicates that the memory traces of the inflected verb types (IL) are distributed in a more "distinct" way within the paradigm, namely, some types (of the paradigm) carry more information than others (e.g. *prijzen* left panel in Figure 3.1). High Inflectional entropy (e.g. *helpen*, right panel in Figure 3.1) describes more "uniform" distributions; memory traces of all types are more similar to each other and carry more or less the same information. Since language processing is sensitive to interference

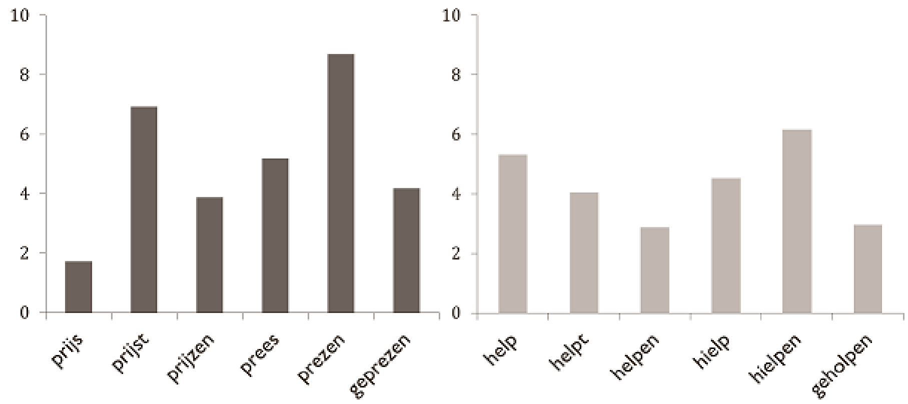


Figure 3.1: Distribution of paradigms with low Inflectional entropy (1.476 bits for Dutch verb *prijzen*, 'to praise') and high Inflectional entropy (2.183 bits for Dutch verb *helpen*, 'to help'). Bars represent the information load of each verb type of the paradigm.

effects, that is, effects arising from neighbouring elements (discussed in Section 2.3), it is only normal to expect that Inflectional entropy should be related to processing cost. In fact, as will be presented in the next section, the value of inflectional entropy can be seen as an index of the amount of "support" a verb form receives from its neighbours and can thus be used to predict how “easy” or “hard” it is to activate a verb, given the paradigm it belongs to. But, *what is the psychological reality of inflectional entropy and how can the distinction between low and high inflectional entropy be relevant for language processing?*

3.4 Empirical work

Imagine that you have two bags full of balls and the balls are identical in size and weight. One bag contains 5 blue balls and one contains 7 balls of different colours. The first bag will be one of higher entropy than the second bag because of the larger similarity of the items it contains. Now you are asked to pick the bag that weighs more. You will need to lift each one and select the heavier one, using some effort for the lift, and you will pick the one with the colourful balls because it contains more (and you will realize it is heavier). Now suppose you are asked to pick the bag containing the highest number of blue balls. The fact that the one bag contains only blue balls will make you, quite quickly, choose that one. The fact that the balls are very similar to each other will facilitate your task. But what will happen when you are asked to pick up from each bag the ball that has the lightest blue colour?

Entropy, that is, the similarity among a members of a network has, generally, a *facilitatory* effect. However, if the task that you have to perform on a high entropy set includes a “search-to-find” operation then this similarity will delay completion of the task.

The studies that employ the tools of Information Theory on language processing have dealt with the information carried on the *suffix* of the inflected forms (Kostić, 1991, 1995, 2013) and with the influence of the neighbours (Moscoso del Prado Martín et al., 2004; Baayen et al., 2006; Milin et al., 2009b) and the results are in line with everyday intuitions. When something is heavy, as a result of the information it carries, it is hard to process. When the neighbours are the same, (speed of) comprehension, which is a perceptual task, is facilitated (since the target word is given there is no "search-to-find"). Production, on the contrary, where one needs to search for the target word to express the intended concept, is delayed by uniform neighbours.

Kostić was the first to note that response latencies of inflected forms, in a language like SerBoCroatian that inflects case and number are better explained by the amount of information the forms contained in their suffixes. He proposed that the computational system is sensitive to the uncertainty it has to deal with and the 'response latency can be now expressed as a function of the amount of information derived from the average frequency per syntactic function within an inflected form of a noun' (Kostić, 1991, pg. 65) resulting in Formula 16. The *syntactic function* is, as mentioned before, a term used to describe the *environments* in which a form can be found. For example, a noun in SerBoCroatian in the accusative case, with the same suffix, can either indicate an instrument (Plasi brat*om*, 'He threatens by means of brother') or an accompaniment, if preceded by a preposition "with" (Plasi sa brat*om* - 'He, with a brother, threatens'). In that sense, response times are described by both frequency of use and linguistic constraints. Kostić calculated the information carried in each form's suffix and found a positive correlation in lexical decision tasks. The more *IL* a form had, the longer it would take to recognize it.

(16) Information Load of a morpheme m:

$$IL_m = -\log_2 \frac{\frac{F_m}{R_m}}{\sum_{j=1}^{c} \frac{F_j}{R_j}}$$

The first who looked at the influence of the paradigm on lexical retrieval for Dutch complex words was Moscoso del Prado Martín (2004), who, to be more precise, used the *Information residual*, a combination of *IL* and what he called the *Paradigmatic entropy* of which *Inflectional entropy* is a part, and found an inhibitory effect. Inflectional entropy, as has been discussed in this work up to now, has been shown to be negatively correlated, in comprehension, with response times for English monosyllabic and monomorphemic words (Baayen et al., 2006), English nouns (Milin et al., 2009b), and verbs in English (Baayen and Moscoso del Prado Martín, 2005), in SerBoCroatian (Kostić and Havelka, 2002) and in Dutch (Tabak et al., 2005, 2010; van Ewijk, 2013).[5][6]

For production however, and as expected, the result was reverse. Response latencies in naming tasks were found to be positively correlated with Inflectional entropy for English inflected words (Baayen and Moscoso del Prado Martín, 2005; Milin et al., 2009b), English verbs (Baayen and Moscoso del Prado Martín, 2005) and inflected Dutch verbs (Tabak et al., 2005, 2010). The different direction of the Inflectional entropy's influence follows from the "search-to-find" operation required for the target word in production.

As mentioned before, researchers until now have investigated the effect of lexical organization (through an information-theoretic approach) for words *in isolation*. This work follows up and looks at the effects of lexicon, mirrored in the speed of lexical access, for verbs in a sentence. In fact, Kostić himself said that an introduction of a new measure would make sense only if it could hold for both words in isolation and *in context* (Kostić, 1991, pg. 63). Quantification of lexical access along with the constraints imposed by memory will give an insight on some (more) factors that play a role in sentence processing.

[5] The studies in (Baayen et al., 2006; Milin et al., 2009b) use Inflectional entropy among a set of other predictors such as Relative entropy, Derivational entropy etc., in order to find the best predictor for RTs. The results mentioned here refer only to the independent effects of Inflectional entropy.

[6] Milin et al. (2009a) found that RTs for SerBoCroatian nouns were better predicted by a combination of the inflectional paradigm and the broader inflectional class, as they found no independent effect of Inflectional entropy. Still, Inflectional entropy *is* included in their predictor which is in line with what has been claimed in the rest of the studies and in the present work: it is not InflH alone that quantifies all the processes of lexical retrieval, but it is a very good estimator.

3.5 Sentence understanding bit by bit

The aim of this section is to summarize the ideas already discussed and put the pieces together towards a quantification of lexical access.

3.5.1 Principles and properties of memory

The various memory models, and the ACT-R framework, agree that representations of our knowledge are stored in long-term memory (LTM) and characterized by a *level of activation* that describes how accessible they are. A representation is *activated* when it passes the threshold and becomes available to Working memory (WM) leaving a *memory trace* of a specific *strength* (see Anderson, 2005a, and references therein). The strength of the trace of a representation of an activated item varies according to how much *effort* was consumed during its activation; an item that was activated *easily* has a *weaker* trace than an item that was hard*er* to activate. What triggers this inverse relation is the fact that the processor makes use of its available resources in as optimal a way as possible, given its limited capacity and its knowledge about the task-related structure. This strategy should not be seen as just a postulation about memory systems. Imagine that you want to paint two pieces of furniture that are at the top floor of a house and your painting utensils are in a small room at the ground floor and cannot be moved from there. Suppose that the one piece of furniture is a heavy closet and the other is a small side table and you bring them both to the ground floor. After you are done, you cannot keep them both because probably you must paint more pieces of furniture from the top floor. Which one would you take back to its position if you knew that you might need to repaint additional parts of the closet or the side table? Probably the side table even if that means that you will be left with a big closet in a small room. This is also what the processor does. When it consumes a lot of resources to activate an item it stores a representation with a strong trace, to avoid repetition of a costly retrieval. On the other hand, for items that are easy to retrieve the trace is weak because it is more economical to re-retrieve them from LTM when they can be easily activated than to consume more resources in making them prominent in WM (Glanzer et al., 1993; Hofmeister, 2011).

What happens when the items are retrieved and represented in WM (or else, what happens in the small room at the ground floor)? What modulates the processing *cost* of each task is a matter of the processes that this task involves and, in fact, this is a matter that is still far from being resolved. However what is important for this work is that *retrieval* of items from WM is sensitive to the *strength* of the items' traces and the possible interference induced by similar stored items. Additionally, a trace is strengthened every time the item is re-addressed. The limited processing resources of WM are distributed according to the demands of each performed task. The *speed* of computations in WM is an interplay between the strength of the traces of the activated items and the ratio $R(esources)_{L(eft)} = \frac{available - consumed}{available}$ resources. Because the processing effort is an additive measure, accumulated processed material might overload the system and $R_L \rightarrow 0$ (but never equals 0, at least for fully developed and non-damaged systems). In that case, the processor reaches its processing limits and even the computations that are "easy" must, temporarily, slow down. In the same sense, computations that are, generally, characterized as "hard", are accelerated by the abundance of resources. *Which are these cases?*

When an item has a weak trace of representation in WM, it has consumed few resources but its re-addressing will be hard. An item with a stronger trace will be re-addressed faster, being however in a system with fewer resources left because of the large amount of effort consumed during its first activation.

Summarizing the properties of LTM and WM:

- The processor has a limited processing capacity.
- The processor is sensitive to $R_L = \frac{avail. - cons.}{avail}$ resources.

- Processing speed is influenced by the amount of R_L and by the trace of the representations.
- The state at which $R_L \to 0$ can slow down computations.
- Easily activated items create a weak trace compared to items that require a lot of processing effort for their activation.
- The speed of re-addressing a stored item in WM depends on the strength of the trace of its representation.
- Possible re-addressing of an item strengthens a trace.

3.5.2 Memory properties on the linguistic domain

As mentioned already in Section 2.3, L&V (Lewis and Vasishth, 2005) applied the properties and principles of memory, based on the ACT-R architecture, to the linguistic domain focusing on WM (Formulas in 9 repeated here as 17). Lexical items are retrieved from LTM and are brought into the FoA to combine into the structure. Just-processed elements are stored in the relevant buffers and have a *Total Activation* (A_i) that describes the ease with which they will be retrieved.[7] *Total Activation* takes into consideration that the activated items are subject to decay and the interference induced by their similarity (S_{ji}) with other activated items as well as the degree of the items' accessibility in LTM (what I called *Activation Potential* in Section 2.3.2). Crucially, L&V estimate the speed of retrieval computationally, as a function of A but they deliberately don't describe that stage further, as it is not in the focus of their study.

(17) Equations of ACT-R

a. Total activation: $A_i = B_i + \sum_j W_j S_{ji}$,

[7]The term *Total Activation* is expressed as A_i in L&V's formulas, but I will sometime refer to it as TA for reasons of simplicity.

b. Associative retrieval interference: $S_{ji} = S - \ln(fan_j)$,
where S is the maximum associated strength and fan_j are the items associated with i in WM

c. Base level of activation: $B_i = \ln(\sum_{j=1}^{n} t_j^{-d})$,
where d is the decay parameter, computationally estimated to be 0.15

d. Retrieval latency: $T_i = Fe^{-A_i}$,
where F is a scaling constant (in L&V's simulations is set to be 0.14)

I will propose a way to approximate the cost of that lexical access, filling in the under-described part of L&V's model, through the quantification of the item's *Activation Potential* using the notions and tools of Information Theory. I will propose that this cost, along with the amount of consumed resources, further influences the processing speed of a sentence, at each processing step. This suggestion will be tested experimentally, in contrast to L&V's model that was tested computationally. I will start from the core and focus on the most prominent element of a sentence, the verb.

3.6 An information-theoretical model for sentence processing

To approach the less well-studied part of lexical access, I assumed in Section 2.3.2 that lexical items are stored in LTM and are characterised by a level of *Activation Potential* (AP), which is determined by the items' frequency, and their connection to other items. The assumption is that it is the amount of an item's *Activation Potential* that indicates how *accessible* the item is in LTM. Lexical items with a high AP are more accessible and can be *activated faster* than lexical items with a low AP. Consequently, although the *Activation Potential* is proportional to the speed of activation, it is *inversely* proportional to the strength of the trace of the activated item's representation in WM.

An item that has low AP has a representation in WM that has a strong trace, as a result of a high consumption of processing effort. In the ACT-R terms this corresponds to a higher *Total Activation*. At the same time, the system is left with fewer resources than when an item with higher AP is activated. To put it simply, weak traces (of items with high AP) exist in a system with a lot of available resources and strong traces (of items with low AP) in one with fewer available resources. Clearly, whether a trace is strong or weak matters only in the cases that the item needs to be *retrieved* from WM, either to fill a gap, as in (18a), or to be operated upon, as in the case of reflexives in (18b).[8]

(18) a. Who does Kalomira love <who> ?
retrieval of *who* to fill the gap in the object position of *love*

b. Kalomira$_i$ loves herself$_i$
re-addressing of *loves* for the interpretations of *herself* [9]

How an item is processed is influenced by the way the lexical item is stored in LTM, which has a direct impact on the resources left in the processing system and on the item's representation in WM. So crucially, organization in LTM affects the processing speed of the *rest* of the sentence. But, *How can we quantify the influence of an item's accessibility, as measured by its Activation Potential, on the processing cost of* a sentence*?*

It follows that the terms that need to be quantified are: i) the Activation Potential, ii) the strength of the trace of the representation and iii) the amount of resources consumed during computations.

I have already described how Information Theory offers a quantita-

[8]Activated items are stored in WM only temporarily, as they are subject to decay. We talk about retrieval only in the short run of sentence processing. In the long run, of say, a conversation, they will, most probably, need to be re-activated from LTM.

[9]The exact process of re-addressing the verb for the interpretation of a reflexive is explained in detail in Section 4.1

tive way to represent messages (or words, sentences, even concepts for that matter) in terms of bits of information. It can quantify them in a linguistics-independent manner, to express the amount of “load” each message carries. Hence, it provides a tool to quantify the terms “memory strength” and “accessibility”, factors that affect processing complexity.

The Activation Potential depends on the ‘Network’s Influence’, as suggested in Section 2.3.2, a term that poses that one of the factors that influence the ease of activation of an item is its connection to its neighbours. Inflectional entropy can describe the distribution of the inflectional paradigm and quantify how probable it is for an item to be activated in relation to its other inflected variants. So, the ‘Network’s Influence’ and the accessibility of an item *for the first time* can be approximated, in information-theoretical terms, by the paradigm’s Inflectional entropy (Formula 19). The term $(-1)^n$ is included in the formula to capture the interaction, mentioned already, between the measure-related principle of entropy and the task-related property of a “search-to-find”operation, namely that sets with high entropy always provide support and facilitation unless the task includes searching. Production would thus correspond to $n = 1$ and comprehension to $n = 0$.

My focus is on comprehension, which means that the activation of an item will be boosted in paradigms where items have, more or less, the same probability of being activated, creating thus, in a sense, an “on guard for activation” network, as experimentally attested and briefly outlined in Section 3.4. Such a network is characterized by a value of high Inflectional entropy. Paradigms characterized by a value of high Inflectional entropy provide their members with a high AP (Formula 20a), facilitate their activation and accelerate processing times. These are exactly the cases that the processor uses less effort and of which it stores a weak trace. So, the strength of the trace in WM of an item’s first activation is *inversely* proportional to its paradigm’s Inflectional entropy and relation (20b) holds. Note that comprehension deals with acoustic or visual *signals*, that is, with *energy* that is transmitted, whereas InflH measure *bits*. Although I have avoided using the term *energy* until now, because it is not used in the literature and I don't have a legitimate way to approach it, it is important to keep it in mind that AP should eventually express unit of energy needed for activation (rather than bits). The constant k in (20b) therefore expresses the amount of energy that is needed to process 1 bit of information.

The *Base level of Activation* (B_i in Formula 17a) makes the *Total Activation* of the item, in WM, higher every time the item is used and expresses both the fact that re-addressing an activated item in WM strengthens its trace and that items in WM are subject to decay. It can also be enhanced with $\frac{1}{InflH}$ to include the effect of lexical access on the activation of the trace. Formula 20c follows. I must say here that I don't want to postulate that AP will be necessarily in an additive relation with B_i, but I do so for reasons of simplicity and demonstration.[10]

(19) Information theoretic quantification of Activation Potential of a lexical item i in LTM:

$$AP_i = (-1)^n \mathit{InflH} \quad \begin{cases} \text{if task} \neq \text{“search-to-find”} \rightarrow n = 0 \\ \text{if task} = \text{“search-to-find”} \rightarrow n = 1 \end{cases}$$

(20) Sentence comprehension ($n = 0$)

a. Information theoretic quantification of Activation Potential of a verb i in LTM:

$$AP_i = \mathit{InflH} = -\sum_{i=1}^{c} \frac{\frac{F_i}{R_i}}{\sum_{j=1}^{c} \frac{F_j}{R_j}} \times \log_2 \frac{\frac{F_i}{R_i}}{\sum_{j=1}^{c} \frac{F_j}{R_j}}$$

b. Strength of the trace of an activated item $= \dfrac{k}{AP_i} = \dfrac{k}{\mathit{InflH}}$

c. Total activation of a verb in WM:

$$A_i = \ln\left(\sum_j t_j^{-d}\right) + \frac{k}{\mathit{InflH}} + \sum_j W_j S_{ji}$$

[10]Actually I believe, that it can be incorporated into the sum of B_i, but this is an issue that falls outside the focus of this work. This term, thus. will not be used as such in explaining the data or in any other way.

I have no way to quantify the amount of resources used during first activation, or re-addressing and I will therefore treat them approximately.

A simple example of the rationale is that if *loves* in (21a) has a higher AP than *adores* in (21b) then *Cruyff,* in (21a) will be read faster than *Cruyff,* in (21b) because the system in the *love*-case has more resources.

(21) a. Kalomira loves Cruyff

b. Kalomira adores Cruyff

The predictions of the model for items with different values of InflH are summarized in Table 3.4.

3.6.1 The Inflectional entropy continuum

From the fact that Inflectional entropy is calculated over the sum of the inflected variants of the paradigm (its size n), it follows that a factor for the speed of lexical access is the morphological *richness* of a language. In fact, languages with poor morphology, like Dutch, have small paradigms of less than ten inflected forms. Just a few verb types occur in a range of syntactic functions and that increases the value of the surface frequency of the ones mostly preferred when compared to the less preferred. The dissimilarity in the distribution results in low*er* values of Inflectional entropy. In contrast, languages with rich morphology (like Greek) have verbs with a large range of paradigm sizes, from 15 up to even more than sixty inflected forms.[11] These languages encode (almost) every feature in the inflectional suffix and have (roughly) a specific inflected verb type per syntactic function. Hence the frequencies of the verb types are, proportionally, more representative (since they are not accumulated over lots of functions) and they have paradigms with high*er* values of Inflectional entropy.

At the same time, Inflectional entropy is measured in bits and can thus form a continuum onto which one can fit a language depending (at

[11] The exact size of the paradigm is not that important. The magnitude of the size is mostly what matters.

Table 3.4: Speed of access depends on the AP of the lexical item. The strength of the trace is proportional to the speed of access. Re-addressing enhances the strength. Speed of re-addressing is modulated by the trace of the "to-be re-addressed lexical item". When there is no re-addressing involved, speed of processing at the second step depends on the amount of resources left in the system. Slow computations require a lot of effort (and resources).

		1^{st} proc. step (from LTM)	2^{nd} proc. step (in WM)	
		1^{st} activation	Re-addressing	No re-addresing
Low AP	speed of access	slow	fast	NA
	strength of trace	strong	strong(er)	strong
	resources used	+ + +	+	depends on the process
	speed of processing at proc. step	fast	slow	
High AP	speed of access	fast	slow	NA
	strength of trace	weak	strong	weak(er)
	resources used	+	+ + +	depends on the process
	speed of processing at proc. step	fast	slow	fast

Note: Number of "+" represents the amount of resources used in each step.

least) on its morphological richness. The reason to do that is that Inflectional entropy is closely related to the processing cost of the activation of verbs. The position of the language in the continuum can reveal information about the amount of resources used by the system for the first stages of lexical activation and thence about the amount of available resources left for further processing of a sentence. Languages that lie on the left side of the continuum (low values) would use more resources during the first activation of lexical items than languages that lie on the right side of the continuum (verbs with higher values of InflH). For the languages under study, Dutch would be positioned on the left side of the InflH continuum whereas Greek would be positioned more to the right side of the continuum.

This observation is important because there is a difference between investigating the influence of lexical access in sentence processing *within* a language and in the continuum (*between* languages). In the former case, one can investigate the speed with which different structures are processed in a system that has the *same* properties. It can give insight on the way its structure is processed in a system that uses a lot of energy during the first activation, like Dutch (or saves energy, like Greek). In the latter case, one looks at two systems that after the first activation have a different amount of resources left, and hence structures can be investigated in relation to the resources they use. Such an analysis would shed light on the priority with which traces and remaining resources are handled by each system with *different* properties. Through that analysis the effects of irrational slow down or excessive acceleration as a result of the amount of the resources left (R_L) can be observed.

3.7 Summary

The key ingredients of the information-theoretical model for sentence processing are:

- High Inflectional entropy, and thus high Activation Potential, helps activation in LTM when there is no "search-to-find" process.

- Activating items with high Activation Potential saves the processing system on resources.
- High Activation Potential results in items having a weak trace in WM.
- Languages that lie on the left side of the continuum (poor morphology, low*er* values of Inflectional entropy) have verbs with lower Activation Potential. They use a lot of resources during the first activation, having however representations with stronger traces.
- Languages that lie on the right side of the continuum (rich morphology, high*er* values of Inflectional entropy) have verbs with higher Activation Potential. They abound with resources and processing is generally faster, but the activated representations have weaker traces.

In what follows, the model will be tested in Dutch and Greek in online experiments. The contrasts will include items with varying values of Activation Potential and two cases with different linguistic requirements. In Chapter 4 the results of the experiments studying the processing of the object in the sentence and the verb's degree of influence will be presented. Chapter 5 will investigate the state of shortage in resource.

CHAPTER 4

Sentence processing and Object types

4.1 The role of inflectional entropy in a sentence

This chapter examines the influence of Inflectional entropy (InflH) in *sentence* processing, at a *within* and a *between* language level. But first, let me recapitulate the main points of the previous chapters that are relevant for the present one.

Inflectional entropy, the information-theoretic measure that describes how the distribution of a paradigm is represented in the mental lexicon, can quantify the *Activation Potential* (AP) of an inflected variant within the paradigm and hence the variant's *accessibility*. Through the value of the AP of an inflected form, one can approximate the speed of the item's retrieval, as described in Section 3.6. More precisely, in comprehension, a perceptual process in which the target is given and there is no "search-to-find" operation, AP is proportional to Inflectional entropy. Verbs with high InflH are thus characterized by a higher level of AP. Indeed, as already reviewed in Section 3.4, and in line with the ACT-R, Inflectional entropy predicts response latencies in lexical identification tasks and the effect is facilitatory. That means that a verb like *prijzen* ('to praise', in Dutch), which belongs to a paradigm with lower InflH is identified as a word more slowly, than a verb like *helpen* ('to help', in Dutch) that belongs to a paradigm with higher InflH (van Ewijk, 2013). These observations on lexical access come however for words in *isolation*. But, *Does the value of Inflectional entropy influence the processing speed of an inflected verb when the verb is part of a sentence?*

For sentence comprehension, as outlined in Chapter 2, three stages, roughly, emerge:

- Stage 1: Activation of lexical items in LTM that become available to the focus of attention (FoA) and working memory (WM)
- Stage 2: Combination of lexical items into a structure and computation of semantic interpretation and
- Stage 3: Application of discourse and world knowledge for the interpretation of the proposition.

To address the aforementioned question, we need to put the verbs into sentences, and I will start with the most basic structure, as the one in (22), in Dutch. While reading a sentence like (22a) (or 22b), the lexical items *Jaco*, *prijst* (*helpt*) and *Loes* are activated in long-term memory (LTM) and become available to working memory (WM) to combine into a language structure (Stage 1).

(22) a. Jaco *prijst* Loes
'Jaco praises Loes'

b. Jaco *helpt* Loes
'Jaco helps Loes'

The word *praises* has lower AP due to the lower Inflectional entropy of its paradigm than (*helps*) that results in longer processing time during its activation. Given that *Jaco* is the same in both instances of (22), if the effect of InflH is preserved when the verb is in context, then the processing speed at the point of the verb will be faster for (22b) than for (22a).

Q2: Is *prijst* in (22a) read more slowly than *helpt* in (22b) as a result of the former's lower value of Inflectional entropy?

Inflectional entropy is associated with the processing speed of lexical access. The processing speed, in turn, depends on the effort consumed and has a direct effect on the amount of processing resources used. I take low speed to reflect costly computations and hence to more effort consumed.[1] Processing cost works, by definition, in an additive way and the the processing system has a specific capacity. If processing A is costlier than processing B, then the system will have less resources left after having processed A than after having processed B, a difference that will also affect the processing speed of subsequent elements. It is thus natural to to expect that if a verb of a clause is activated faster than another verb in the clause, that the speed of processing e.g. the object of the sentence will also be influenced.

Q3: Is *Loes*, in (22) processed with a different speed when it is an object of a *prijzen*-type verb (lower InflH) than when it is the object of a *helpen*-like verb (higher InflH)?

At the same time, processing cost is modulated by the constraints that the linguistic expressions impose. Expressions with different requirements that can be used in the object position should be processed accordingly. To exemplify this, consider the contrast in (23):

[1]Kostić (p.c.) takes a different view on the issue. He suggests that high speed reflects high consumption of resources. He assumes when something is really unexpected one puts all of his/her resources to perceive it. For example, when a lion crosses an avenue and we try to figure out what happens, we react faster than when we see something that is "regular", like a man crossing an avenue. Although the predictions of this rationale are the same, for the focus of study of this chapter, it might be problematic on explaining the data presented in Chapter 5.

(23) a. Jaco prijst Loes
'Jaco praises Loes'

b. Jaco prijst zichzelf
'Jaco praises himself'

Loes and *zichzelf* in (23) are both in the object position of the sentence and act as the receiver of the "praising". The way that each get an interpretation, though, is different. As briefly discussed in Chapter 1, *zichzelf*, cannot get interpreted unless it builds a *dependency* with an antecedent within a sentence from which it can inherit a referent, a process that is not needed for the interpretation of an proper name, like *Loes*.

For the interpretation of the reflexive, I follow Reuland and Winter (2009) and Reuland (2011) and take *zichzelf* to be an underspecified nominal phrase consisting of the (defective) pronominal *zich* and the SELF-marker *zelf*, structurally represented as in (24).

The SELF marker reflexivizes the transitive verb (e.g. praise) and makes it a self-predicate (e.g. self-praise). *Zich* is interpreted through binding by the external argument (here, informally represented by co-indexation). The precise syntactic mechanisms don't concern us here (see Reuland, 2011, for details).

(24) DP zich [NP zelf]

(25) Loes$_i$ prijst zichzelf
Loes$_i$ prijst [DP zich$_i$ [NP zelf]] $\Rightarrow$
Loes$_i$ [zelf-prijst] zich$_i$
Loes$_i$ [SELF-praises] her$_i$
'Loes praises herself'

What is essential for this study, is that *zichzelf* operates *on* the verb, changing its theta-grid from a transitive to a reflexive verb, and is interpreted through a dependency with the subject.[2]

Coming back to the example in (23), the proper name *Loes* must introduce a new (female) entity in the discourse and the event of "Jaco's-

[2]For the precise formal analysis see Reuland and Winter (2009) and Reuland (2011).

praising-of-Loes" is created. The interpretation of *zichzelf*, on the other hand, needs to re-address the verb (stage 2) and access *Jaco* in order to get a referent, creating the "Self-praising Jaco" event. So, processing the object in (23b) involves this re-addressing operation on the verb, which, as mentioned in Section 3.5.1, enhances the strength of the trace of the activated item in WM, and is absent in the case of 23a. If my suggestion in Section 3.6 holds, namely that the Inflectional entropy (and the AP) must also influence the *Total Activation* of the item activated in WM, then the processing cost between *zichzelf* and *Loes* should differ. Or else,

Q4: Is *zichzelf* processed with a different speed when it is an object of a *prijzen*-type verb (lower InflH) than when it is the object of a *helpen*-like verb (higher InflH)?

Q5: Does the interpretation of an anaphoric expression like *zichzelf* require an operation on the verb?

Q6: Is the introduction of a referent in the discourse in the case of a proper name like *Loes* a costly operation?

Lastly, Inflectional entropy is a measure that highly depends on how large the inflectional paradigm of a verb is, making it a language-dependent measure (as described in Section 3.6.1). Since InflH depends on the morphological richness of a paradigm and is connected to the processing cost of verb retrieval, modulating thus the resources that are left after the verb's first activation, one more question that follows is:

Q7: How does Inflectional entropy affects processing speed in morphologically richer languages?

This chapter investigates the degree to which, difficulty in processing of a lexical item induces difficulty in processing of the subsequent ones considering the trade off between processing resources and interpretative requirements of the lexical items involved..

4.1.1 Concepts to keep in mind

Summing up the main things to keep in mind before continue to the presentation of the experiments and the results:

- Inflectional entropy describes the way the inflectional paradigm is organized in LTM.
- High Inflectional entropy reflects a uniform paradigm and low Inflectional entropy reflects a less uniform paradigm.
- Inflectional entropy is one of the factors that influence a lexical item's accessibility, as measured by the item's Activation Potential.
- When there is no "search-to-find" operation involved, InflH is proportional to AP.
- Verb forms of "uniformly" distributed paradigms (high InflH) have higher AP and are retrieved faster. Verb forms of less "uniform" paradigms (low InflH) have lower AP and need more effort to be activated.
- The strength of the trace of the representation of an activated verb forms in WM depends on their ease of access. When activation is easy (high InflH) the representation has a weaker trace than when activation is hard.
- The speed of re-addressing a representation's trace in WM is subject to its strength.
- Inflectional entropy provides an indication of the available resources of the WM system during computations.
- Inflectional entropy can describe the available energy during computations across languages, depending on the size of their morphological system.

In the following section two self-paced reading experiments will be presented that were designed in order to address Q2-Q6 and investigate the way that the organization of the inflectional paradigm influences processing of a sentence at each processing step.

4.2 Experimental approach

The main assumption is that processing speed is modulated by a trade off between the speed of activation and the available processing resources of the computational system. The relevant principles regarding WM are:

Principle 1: Shortage in available processing resources delays computations.

Principle 2: Effort is an additive measure in the sense that each process adds up on the effort already exerted.

The claims made are:

Claim 1: Inflectional entropy is one of the factors that influence the Activation Potential of an item and as such it influences the strength of representation of the activated item in WM.

Claim 2: The strength of the representation trace of an item stored in WM depends on the processing effort spent during its activation. When processing is *hard*, then the trace is *strong*.

To address Q2 to Q6, as posed in the introduction of this chapter, verbs of different InflH were put into a sentence and the type of their object was contrasted. In one condition the interpretation of the subject required a syntactic dependency and on the other condition it did not. The idea of the experimental design see Table 4.1.

4.2.1 Experimental method

The same experimental method is used in all the experiments presented in this dissertation. The online word by word moving window self-paced reading paradigm (Just et al., 1982) was employed to study the speed of sentence processing. In this paradigm the sentence is first displayed as a series of dashes on the screen, each one representing a word in the sentence. Participants are asked to press a button (the space bar),

Table 4.1: Design of experimental items where l stands for lower and h for higher Inflectional entropy, *PN* for proper name and *R* for reflexive.

	example	verb position in the entropy continuum	syntactic dependency
l-PN	Jaco praises Loes	low*er*	−
l-R	Jaco praises himself	low*er*	+
h-PN	Jaco helps Loes	high*er*	−
h-R	Jaco helps himself	high*er*	+

each press of which, replaces the dash with a word of the sentence. Subsequent button presses replace the previous word by a dash while the current word is shown. Only one word is visible at any given time. The participants are instructed to read as fast as possible, making sure that they comprehend the sentence. This method allows readers to control the speed with which they read a text. The latencies of the button are shown to correlate with the time course of the cognitive processes during reading and text comprehension (Just and Carpenter, 1980) and they will serve as the measure unit. The experiment was presented using the ZEP experimental software (Veenker, 2011).

Self-paced reading is pretty simple to implement, but also an adequately accurate method to capture subtle alterations in comprehension of linguistic stimuli. At the word level at least, the method is able to register effects that are generally similar with those obtained through methods that are thought to be more sensitive and more natural, such as eye-tracking (Just et al., 1982; Rinck et al., 2003).

4.3 Experiment I (Dutch)

Starting from the finding that *prijzen* ('to praise', in Dutch) is retrieved more slowly than *helpen* ('to praise', in Dutch) because of its lower value of Inflectional Entropy (van Ewijk, 2013). Since InflH is a language-dependent measure, the first experiment was conducted in Dutch to allow direct comparison with the results of the lexical decision tasks of van Ewijk (2013). The predictions follow from the model presented in Section 3.6 and the first two columns in Figure 3.4:

P1 Verbs with low InflH will be processed slower than verbs with high InflH, as a result of their different Activation Potential in LTM.

P2 The condition with the dependency will be processed faster in the verbs with low InflH, as a result of the stronger trace of their representation in WM.

4.3.1 Experiment I: design & material

Twenty-four Dutch transitive verbs were used in two conditions; with a referentially dependent object (reflexive, +d) and with a non referentially dependent object (proper name, −d), resulting in forty-eight experimental items. An example of the experimental sentences can be seen in (26).

(26) Hij vleit, in de meeste gevallen, zichzelf/ Eric en niet de
he flatters in the most cases himself/ Eric and not the
andere sprekers na een goede presentatie.
other speakers after a good presentation.

'In most cases, he flatters himself/Eric after a good presentation, rather than the other speakers.'

All experimental items were reviewed and judged by five independent native speakers of Dutch, in a scale of 0 to 5 (denoting a range of "unacceptable" to "plausible"). Only items ranked with a 4 or 5 grade of plausibility were included in the experiment. The Inflectional entropy (InflH) of each verb was calculated as described in Section 3.3 (Table 3.3) and the values ranged from 1.043 to 2.323 bits, with a mean of 1.863 bits (Table 4.2). Every participant saw all the experimental items. The structure of the experimental items is shown in Table 4.3. A strong pronoun *hij/zij* ('he/she', in Dutch) was used in subject position. The

Table 4.2: Experimental design for Experiment I (Dutch). Each participant saw all the 48 experimental items (repeated measures design).

Items	#	Object type	*total*
	24	2 (+d, −d)	48
InflH	*Min*	*Max*	*Mean*
	1.043 bits	2.323 bits	1.863

object position was filled, in the relevant condition with, half masculine and half feminine, proper names, controlled for frequency and length, at the syllable level, with the reflexive (2 syllables as *zichzelf*). All the intervening words between the verb and the object (regions 3 to 6) were kept identical, ensuring that processing cost was constant across items. The critical regions are: the region of the *verb* (region 2) and the region of the *object* (region 7). Additionally, two regions after the object (regions 8 to 11), were included and kept constant across items to capture spillover effects. Sentences continued after the spill over regions to avoid end of a sentence effect (Abrams and Bever, 1969; Just and Carpenter, 1980) and to add to the sentences' plausibility.

Eighty filler items, taken from another experiment, were used as distractors. 60% of the total 128 items were followed by a comprehension statement in which the participants had to judge it as true or false, given the preceding sentence. Eight items that did not resemble any of the items in the actual task were used as practice to familiarize participants with the self-paced reading task.

4.3.2 Participants

Forty-five students of Utrecht University, ten of them male, aged 21;0-29;1 (mean age: 22;5, year; months) were paid to participate in the experiment. All were native speakers of Dutch and were naive as to the purpose of the study. They completed the experiment in a soundproof booth at the lab facilities of Utrecht institute of Linguistics OTS, in one

Table 4.3: Structure of experimental items for the experiment in Dutch. *R* stands for reflexive and *PN* for proper name. Critical regions are marked bold.

He/She Verb *in the most cases* Object *and not the other NP*					
region	1	**2**	3 4 5 6	**7**	8 9 10 11 12
+d: R −d: PN	Hij/Zij	**verb**	in de meeste gefallen	**zichzelf** **Loes**	en niet de andere NP
InflH		varying	constant		controlled

session of maximum 25-minutes.

4.3.3 Data analyses for Experiment I

After preliminary analyses of the data, one participant that didn't pass the 85% threshold in correct answers to the comprehension questions was removed. The results presented are thus over data collected from 44 subjects.

Unrealistic reading times (RTs), below 100 ms and above 2500 ms, and observations that were three standard deviations above or below item and subject mean were excluded from the analysis ($<$ 1% of the observations). The remaining observations were log-transformed to approximate normality and were crossed with Inflectional entropy and Object type as fixed factors with random slopes for participant and item, and analysed using Linear mixed-effect model (Baayen et al., 2008). As already mentioned, to ensure that the observed results will be over-and-above benchmark effects such as frequency, length, placement in the sentence, words used in the verb and the object position were balanced for frequency and number of syllables, as well as position within the sentence (it was kept constant across items) during the design of the experimental items. To account for possible variance due to learning during the task because of the different length of words in the two languages, fixed terms of the log-transformed position of the item in the experiment, and the number of characters of each word were added . Results will be presented per region, including the critical and the spillover regions (when significant effects appear) of verb and object.

4.3.4 Results of Experiment I

There was a very strong effect ($p < .001$) of the logarithmic term of position of the item in the experiment in all regions suggesting a large effect of learning.

Verb

Region 2: region of the verb.

The effect of InflH on reading times did not reach significance.

Region 3: 1^{st} spill over region after the verb.

The effect of InflH observed at the region after the verb was marginally significant ($\beta = -.028, SE = .0165, t = -1.72, p < .08$). Reading times become faster in higher values of Inflectional entropy as seen in Figure 4.1. **Object**

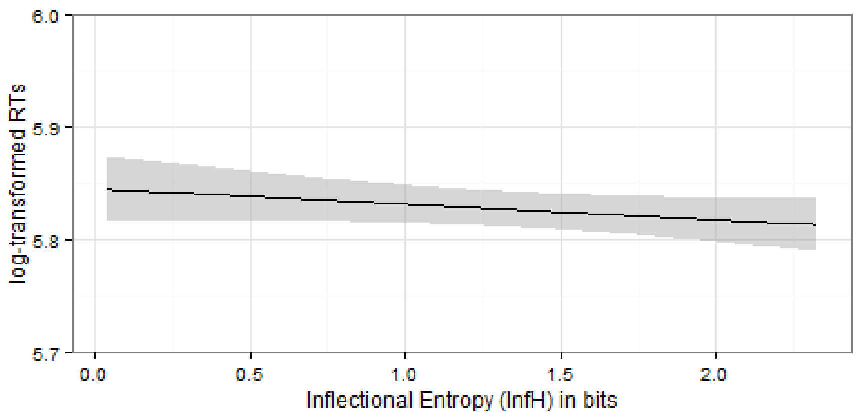


Figure 4.1: (Dutch) First spillover region after the verb
Higher values of inflectional entropy marginally facilitate reading times. Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the logRTs.

Region 7: object region.
No main effects or interaction of InflH and Object type on reading times were observed at the region of the object.

Region 8: 1^{st} spillover region after the object.
There is a main effect of Object type on reading times ($\beta = -.025, SE = -.002, t = -4.358, p = 0$): reflexives are read faster than proper names. Additionally, a marginal interaction of Object type and InflH on RTs is attested ($t = 1.73, p < .07$). RTs for reflexives become slower in higher values of InflH while RTs for proper names become faster when the value of InflH increases (Figure 4.2).

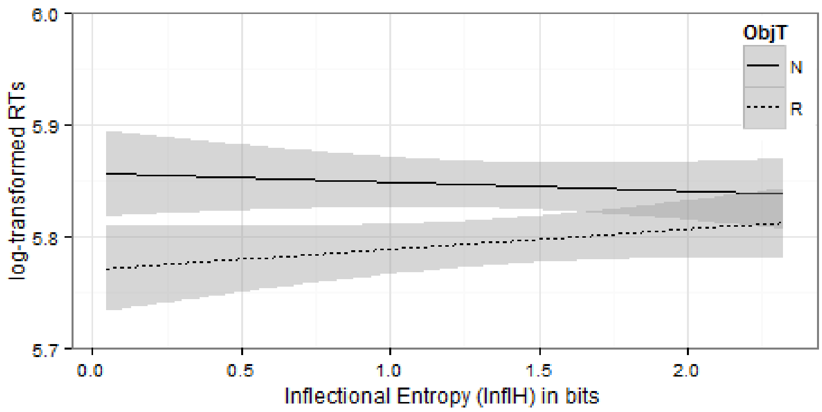


Figure 4.2: (Dutch) First spillover region after the object
Marginal effect of Object type and interaction between InflH and Object type. Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the logRTs for each Object type condition ('N'= proper name and 'R'=reflexive).

4.3.5 Summary of Experiment I

One spill over region of the verb, higher values of Inflectional entropy facilitate processing speed. P1 is borne out: verbs with higher InflH are processed faster than verbs with lower InflH, also *within* a sentence.

Although the result is not that strong as the one attested in lexical decision tasks (van Ewijk, 2013), it still suggests that InflH of a verb influences its level of Activation Potential (as suggested in Section 3.6) and, consequently its processing speed within a sentence. The existence of the interaction between the InflH and Object type shows that the requirements of interpretation of the object *do* play a role in the speed with which it is processed. Moreover, the fact that the speed of processing the reflexive depends on how the main verb of the sentence was processed confirms the hypothesis that the interpretation of the reflexive requires an operation *on* the verb. Interpretation of the reflexive requires re-addressing the main verb and its processing speed is influenced by the strength of the verb's trace of representation. Strong traces of verbs that were, by hypothesis, difficult to activate (low InflH) will be accessed faster than weaker traces of verbs that were activated easily (high InflH) resulting in faster processing of reflexive as an object of a low InflH verb and is borne out. Proper names, that do not have to re-address the verb, add on to the complexity of the sentence. The fact that they are so late in the lower values of InflH suggests that introducing a PN is costly and becomes even costlier when it has to be attached to a verb that has consumed a lot of resources during its activation. This is the first indication that when resources are few, computations slow down even more.[3]

The answers to the questions posed in Section 4.1 are:

A2: *prijst* in (22a) is read more slowly than *helpt* in (22b) as a result of its lower AP, determined by the lower InfH of the paradigm of *prijzen*.

A3: *Loes* is read more slowly when it is an object of a *prijzen*-type

[3] In the published version of this study (Manika et al., 2014) the effects were stronger as a result of a different method of analysis. The data were analysed using Repeated Measures ANOVA using the SPSS statistical package. This method does not account for the variability induced by subjects and items as the LMER which was the main reason I chose to present the results obtained with the latter, even with the accompanied sacrifice of some significant effects.

verb (lower InflH) than when it is the object of a *helpen*-like verb (higher InflH). Processing of proper names is facilitated in higher values of Inflectional entropy, as a result of the higher availability of resources.

A4: *zichzelf* is processed faster when it is an object of a *prijzen*-type verb (lower InflH) than when it is the object of a *helpen*-like verb (higher InflH).

A5: Interpretation of an anaphoric pronoun like *zichzelf* requires an operation on the verb.

A6: Identifying a referent in the discourse for a proper name like *Loes* is costly.

The next section will address Q7 and explore whether the influence of InflH on processing of a sentence, observed in Experiment I, holds in a morphologically rich language like Greek. Greek has verbs with higher values of InflH that increase their overall AP and thus consume less resources during activation. Processing of a sentence is expected to be (relatively) accelerated by the amount of resources available to the system.

4.4 Experiment II (Greek)

The following experiment is a "translation" of Experiment I into Greek because Greek is a language that is morphologically rich, a property that has direct effect on the values of the Inflectional entropies of its verbs (and on the level of their AP). As discussed in Section 3.6.1, languages that have distinct inflected verb forms, and hence large verbal inflectional paradigms, are positioned on the right side of the entropy continuum. This means that Greek verbs should be activated, overall, faster and more importantly, use fewer resources during the first activation, leaving the system with more resources for further computations. Therefore, although a facilitation in the high values of InflH is expected at the verb region, no interaction is expected between InflH and Object type in the object region, contrary to what was attested in Dutch.[4]

4.4.1 Experiment II: design & material

Sixteen Greek transitive verbs were selected and used, like in Experiment I for Dutch, in two conditions; with a referentially dependent object (reflexive, +d) and with a non referentially dependent object (proper name, −d), resulting in thirty-two experimental items. An example of the experimental sentences can be seen in (27).

(27) I Eleni katighori se meghalitero vathmo ton eafto
the Eleni blames in greater degree the self
tis /ton Apostoli para tus kathiyites tis
hers.CL.GEN /the Apostolis rather than the teachers
ya tus kakus vathmus.
hers.CL.GEN for the bad marks.

'Helen mostly blames herself/ Apostolis rather than her teachers for the bad marks.'

All experimental items were reviewed and judged, in a scale of 0-5 (denoting a range of "unacceptable" to "plausible"), by 5 independent native speakers of Greek. Only the items ranked with a 4 or 5 grade of plausibility were included in the experiment. The values of Inflectional entropy were calculated as exemplified in Section (3.2), and ranged from 2.403 to 4.217 bits (*mean* 3.607 bits). For an example of the calculations for Greek, the list of the verbs used and the corresponding InflH values see

[4]By "more resources", I mean, by no means, that languages with poor morphology do not leave enough resources to process a sentence to an extent that the interlocutors will not *understand*. Of course Dutch and Greek speakers will process sentences in a normal pace in conversations. The "delays" that I try to detect are very subtle and happen in the very first stages of processing (and thus, understanding) and the claim is that in a computational system that processes Greek, although less effort is used during the first stages of processing (i.e. during activation of the verb) this might lead to more effert needed in subsequent stages (i.e. because of weak traces that need to be re-addressed or even re-activated).

Appendix A.[5] Each participant saw the whole list of experimental items in a repeated measure design. For the summary of the design see Table 4.4.

Table 4.4: Experimental design for Experiment II (Greek). Each participant saw all the 48 experimental items (repeated measures design).

Items	#	Object Type	*total*
	24	2 ($+d$, $-d$)	48
InflH	*Min*	*Max*	Mean
	2.403 bits	4.217 bits	3.607 bits

The structure of the experimental items is shown in Table 4.5. In Greek, due to the fact that is a pro drop language, a proper name was used in the subject position, instead of a strong pronoun that was used in the Dutch experiment. In particular, eight common Greek proper names were used in the subject position, half masculine and half feminine (so participants saw the same name twice in the experimental construction during the task) that differed by maximally one syllable. The object position was filled, in the relevant condition, also with, half masculine and half feminine, proper names which had roughly the same frequency and they were of the same length, at the syllable level, with the reflexive (five syllables as the reflexive *ton eafto tou/ tis*). All the intervening words between the verb and the object (regions 2 to 5) were kept identical, ensuring that the expected processing cost remains constant across items. The critical regions are: the point of the verb (region 2) and the point of the object (region 6). Regions after the object (regions 7 to 9) were included and kept constant across items to capture spillover effects. Sentences continued after the spill over regions to avoid end of a sentence effect (Abrams and Bever, 1969; Just and Carpenter, 1980) and to add

[5] The frequencies were taken from the Hellenic National Corpus (http://hnc.ilsp.gr), a corpus that has been developed by the Institute for Language and Speech Processing and currently contains more than 47.000.000 words of written texts.

to their plausibility.

Eighty filler sentences of similar length and complexity were used as distractors. Sixty percent of the all items were followed by a comprehension statement in which the participants had to judge it as true or false, given the preceding sentence.

Eight items that did not resemble any of the items in the actual task were used as practice to familiarize participants with the self-paced reading task.

Table 4.5: Structure of experimental items for Experiment II, in Greek. *R* stands for reflexive and *PN* for proper name.

'Helen VERB in a greater degree OBJECT and not her other NP'					
region	1	**2**	3 to 5	**6**	7 to 11
+d: R	I Eleni	**verb**	se megalitero vathmo	**ton eafto tis**	para tus allus NP tis
−d: PN				**ton Apostoli**	
		varying InflH	constant InflH		controlled InflH

The predictions are:

P3 Verbs with low InflH will be processed slower than verbs with high InflH, as a result of their different Activation Potential in LTM

P4 Unlike Dutch, no interaction is expected during the processing of the object, as a result of the abundance in processing resources, due to the higher InflH in Greek, compared to Dutch.

4.4.2 Participants

Thirty-eight students (eight of them male) of the University of Athens, aged 19;1 to 29 (mean age: 22;5, years; months) were paid to participate in the experiment. All were native speakers of Greek and were naive as to the purpose of the study. They were tested on a 13-inch Toshiba laptop in a quiet room of the University of Athens. Each participant completed the task in one session in maximum 25 minutes.

4.4.3 Data analyses for Experiment II

Three participants that did not pass the 85% threshold in correct answers to the comprehension questions were removed from the analyses. The analyses presented are on the data collected from the remaining 32 participants.

Unrealistic reading times (RTs), below 100 ms and above 2500 ms, and observations that were three standard deviations above or below overall item and subject mean were excluded from the analyses ($< 1\%$ of the observations). The remaining observations were log-transformed to approximate normality and were crossed with Inflectional entropy and Object type as fixed factors with random slopes for participant and item and analysed using Linear mixed-effect model (Baayen et al., 2008). As in the Dutch Experiment I, the regions that contained words that varied across the experimental items were controlled for word length (at a syllable level) and frequency during the design of the experimental items. Furthermore, to account for possible variance due to learning during the task and to the possible effect of character length of words, fixed terms of the log-transformed position of the item in the experiment and the number of characters of each word were added. Results will be presented per region, including the critical and the spillover regions of verb and object (in case significant effects arise).

4.4.4 Results of Experiment II

There was a very strong effect ($p < .001$) of the logarithmic term of position of the item in the experiment in all regions suggesting a large effect of learning.

Verb

Region 2: region of the verb.

The effect of InflH on reading times did not reach significance.

Region 3: 1^{st} spill over region after the verb.

A main facilitatory effect of Inflectional entropy was attested at the first spillover region of the verb ($\beta = -.028, SE = .015, t = -1.947, p < .05$). Higher values of Inflectional entropy facilitated processing of the verb. Data are plotted in Figure 4.3.

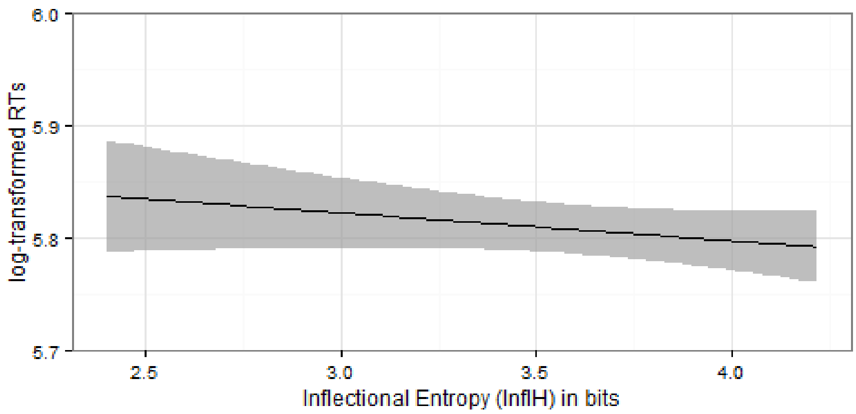


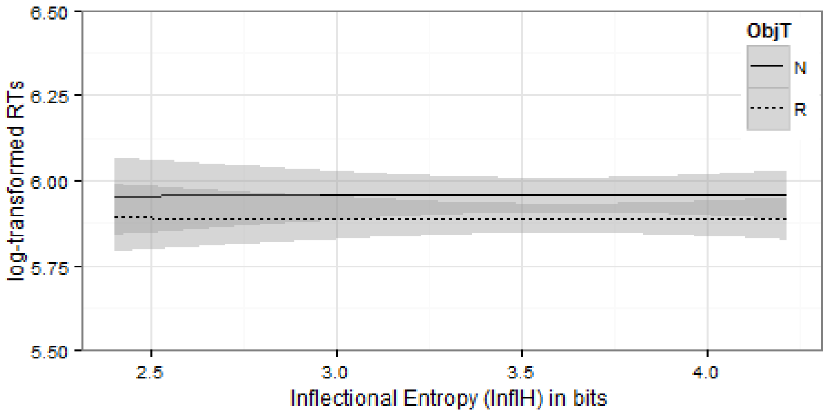
Figure 4.3: (Greek) First spillover region after the verb
Reading times become faster in the higher values of Inflectional entropy suggesting a facilitation in processing of the verb as a result of its high InflH. Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the logRTs.

Object

Region 6 & 7: object region and one spill over region after it.

There was a main effect of Object type for both regions 6 &7 ($t = -2.573, p < .01$ and $t = -4.223, p < .0001$). Reflexives were read significantly faster than proper names as seen in Figures 4.4a and 4.4b for region 6 and 7, respectively. There was no interaction effect observed.

(a) object region 6



(b) spill over region 7

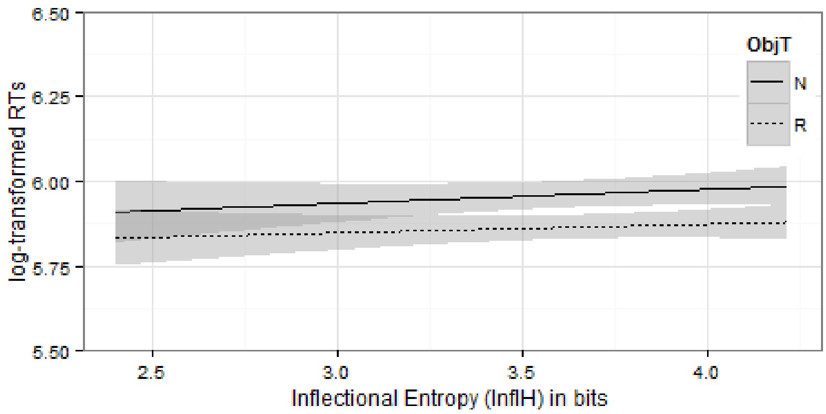


Figure 4.4: (Greek)Object region & first spillover region after it Reflexives are read overall significantly faster than proper names, independent of the value of Inflectional entropy in both the region of the object (top) and one spill over region after it (down). Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the logRTs for each Object type condition ('N'= proper name and 'R'=reflexive).

4.4.5 Summary of Experiment II

In Greek there is also a facilitation of Inflectional entropy in processing the verb for the first time, similar to the one observed for Dutch. Verbs of higher Inflectional entropy are read faster than those with lower values of Inflectional entropy justifying P3, namely that the InflH of a lexical item is proportional to its Activation Potential. In the object position, P4 was borne out: unlike Dutch, in Greek there is no interaction between the processing of objects with different requirements and the values of InflH. The fact that the values of InflH of Greek are higher than in Dutch means that the computational system uses less resources during the first activation of the verb, leaving the system with more resources for further computations. I thus assume, this lack of interaction to be a "ceiling effect", in the sense that, for independent reasons, referentially-dependent objects are processed equally fast in the whole range of InflH. For lower values of InflH for Greek the strength of the "to-be-addressed" verb is strong so processing is fast. For the higher values of InflH, on the other hand, although the trace of the verb is very weak, re-addressing is boosted by the abundance in processing resources. I will come back to that in the next chapter (Chapter 5).

4.5 Summary of results from Experiments I & II

The data obtained from Experiments I & II, as just presented, show how differences in the values of Inflectional entropy of verbs *within* a language (having controlled for all the known factors that influence sentence processing, such as word lenght, frequency and position of the word in the sentence) determine how two structures that contain objects with different interpretative requirements (referentially dependent versus referentially independent) are processed *within* a language. As already mentioned, the speed of processing the object of a sentence depends on the amount of available processing resources and on the object's interpretative requirements. Reflexives need to operate on the verb (since their processing speed depends on how the main verb was processed) to get interpreted and so their processing speed depends on the trace of the verb's representation in WM, contrary to proper names that do not require such an operation. Strong traces correspond to verbs that were hard to activate due to their lower AP (low InflH) but can be easily re-addressed when needed by the reflexive. Such a system that has processed verbs with low value of InflH has used a lot of resources during first activation and has fewer resources left, a state that might delay further processing. Similarly, weak traces might be hard to re-address, but they are still "visible" enough in a system that has a lot of resources left (column 2 in Table 3.4).

As already mentioned in Section 3.6.1, Inflectional entropy can give insight in processing at an additional level, the *between* language level. Languages, depending on their verbal morphological richness lie in a different position in the Inflectional entropy continuum, a position that provides information on the amount of available processing resources that the system will have after first activation of the verbs. Dutch, lies to the left side, with lower values of InflH and Greek on the right side with higher values of InflH, a property that has a direct bearing on the processing effort of the *same* structure in two *different* languages. Furthermore, as the values of InflH do not overlap, analysing the data as coming from the same language can give an insight in the way that the computational system distributes its resources in the course of sentence processing. In the next section I will discuss how proper names and reflexives are processed depending on the language and when the computational system reaches the point of having very few resources.

4.6 Between-languages: Experiments I & II

To compare the two languages all data were merged into one data set and the raw RTs, for each region, were log-transformed to approximate normality. Regions were recoded for the analyses because of the difference in the position of the critical region in the two experiments in each language (region 7 in Dutch and region 6 for Greek). Hence, in the merged dataset, *Obj* corresponds to region 7 for Dutch and 6 for Greek, region *Obj1* to region 8 for Dutch and 7 in Greek etc.

Linear mixed-effect models (Baayen et al., 2008) were fitted in the log-transformed RTs (logRTs) in each region. For the regions before the object, logRTs were regressed against InlfH and Language. The two variables were not inserted into the same model because they represent similar factors and collinearity emerges. After all, language can be seen as categorical predictor for InflH. For the regions from the object onwards logRTs were regressed against InflH crossed with Object type and Language crossed with Object type. Random slopes for participant and item were included in all models. Furthermore, fixed terms of the log-transformed position of the item in the experiment and the number of characters of each word were added to account for possible variance due to learning during the task or to the different length of words in the two languages. Results will be presented by region of interest including the critical and the spillover regions of verb and object.

4.6.1 Results of between-language analyses

There was a very strong effect ($p < .001$) of the logarithmic term of position of the item in the experiment in all regions indicating a large effect of learning.

Verb

Region 2: region of the verb.
The effect of InflH on reading times did not reach significance.

Region Vb1: 1^{st} spillover region after the verb.
Language has no effect on logRTs, which is expected since the analyses of the separate experiments yielded the same effects. The main effect

of InflH is facilitatory ($\beta = -.025, SE = .012, t = -1.972, p < .05$) at the first spillover region after the verb. RTs are getting faster when the Inflectional entropy gets higher as seen in Figure 4.5.

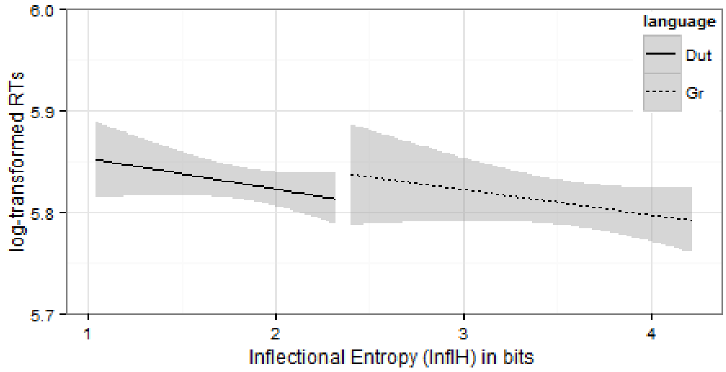


Figure 4.5: (Between languages) FIRST SPILLOVER REGION AFTER THE VERB Inflectional entropy facilitates reading times and the effect holds for both languages. Regression line fitted per language: straight line for Dutch and dotted line for Greek. Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the logRTs.

Object

Region Obj: region of the object.

At the region of the object there was a reliable interaction of Language by Object type on RTs ($\beta = -.014, SE = .007, t = -2.276, p < 0.03$). Reflexives in Greek are processed significantly faster than reflexives in Dutch. At the same time, proper names in Greek were read significantly more slowly than in Dutch. As it will be explained below, this is a result of the two PNs present in the Greek experiment contrary to the Dutch one and not an indication of the processing of the PNs per se. The data are plotted in Figure 4.6.

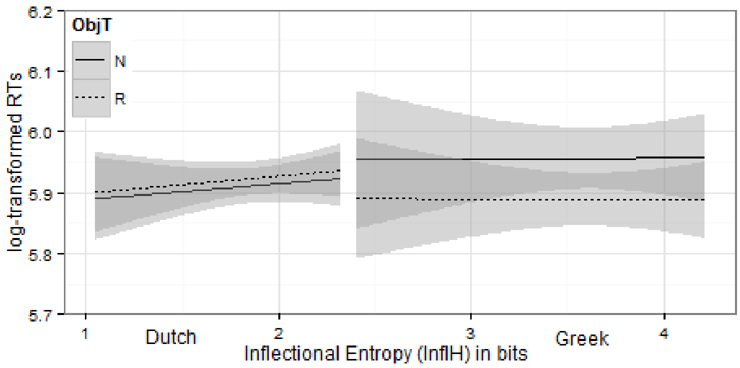


Figure 4.6: (Between languages) Object region
Greek reflexives are processed faster than Dutch reflexives and Greek proper names. Similarly, Greek proper names are processed more slowly than Dutch proper names. Regression lines are fitted per language. Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the logRTs for each Object type condition ('N'= proper name and 'R'=reflexive).

Region Obj1: First spillover region after the object.
A reliable effect of of Object type is attested as proper names were read significantly more slowly than reflexives ($\beta = -.04, SE = .02, t = 2.971, p < .01$). A significant Language by Object type interaction was, additionally, observed ($\beta = -.03, SE = .013, t = 2.167, p < .03$). Results are plotted in Figure 4.7.

4.7 Discussion

The within-language analyses (Sections 4.3.4 & 4.4.4) give an insight in the way that the *Activation Potential* of a verb influences the verb's processing but also that of the object of the sentence. The between-language analyses (Section 4.6.1) provide information about how the same structure is processed in different languages, but also (some) indication of how the processing system distributes its resources.

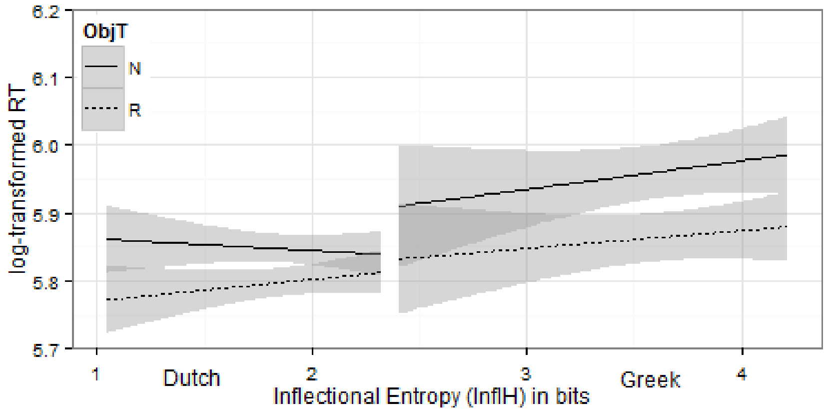


Figure 4.7: (Between lang.) FIRST SPILLOVER REGION AFTER THE OBJECT For Dutch, reflexives are faster than proper names in the lower values of entropy, but RTs becomes slower when the values of Inflectional entropy increase. Proper names on the other hand are read more slowly in the low values of InflH and faster when InflH increases. In Greek, reflexives are read overall faster that proper names. ('N'= proper name and 'R'=reflexive).

The *Inflectional entropy* of the verb's paradigm, one of the factors that influence the verb's AP, is negatively correlated with processing times. The higher the value of Inflectional entropy a verb has, the faster is the verb activated in LTM (lower RTs). Processing of the object is subject to the lexical expression's interpretative requirements. In the case of a referentially-dependent expression, like the anaphoric pronoun, where re-addressing of the verb is required, speed of processing depends on the strength of the verb's trace. The trace of the verb's representation does not matter for the PN, as it does not need to operate on it and therefore the direction of the RTs doesn't change.

The fact that processing the reflexive object, in Dutch, depends on how the main verb was processed when it is an object of a verb with high InflH (Figure 4.2) indicates that the interpretation of the reflexive requires and operation on the verb. Reading times for the reflexive condition slow down when the reflexive is an object of a verb with high

InflH because such a verb has a weak representational trace in WM and re-addressing it requires a lot of processing effort. Processing of reflexives in the Greek experiment do not seem to depend on the speed of processing the main verb and on its InflH. Of course, it might be the case that Greek reflexives do not operate on the verb but it can also be, and it will be shown in the next chapter, that reflexives in Greek *do* re-address the verb but their processing is boosted because of the abundance in resources. Recall that Greek verbs have overall higher values of InflH that Dutch verbs and use fewer resources during first activation, leaving the processor with a lot of resources and making the costly re-addressing process on the verb not detectable, at least with that particular task in the small range of InflH used. In fact, when the range of the values of InflH becomes larger, as in the case of the between-language analyses, the process of the costly re-addressing of the verb for the interpretation of the object when the values of Inflh increase is visible for both languages (recall effect of InflH in Figure 4.7). Processing of proper names, being a costly operation, adds on the cost of the already-processed sentence, and reduces the available processing resources, giving reflexives an advantage of processing speed in all regions. The effect at the verb region is, however, not as strong as expected. A possible reason for that could be the fact that all the sentences in the experiment, both experimental and filler ones, were in the present tense. The fact that no other tense was used might have influenced the way that the paradigms are activated in the sense that present tense will be more active (given the great attested learning), changing the "real" value of InflH that the paradigms have in their idle, stored state. The experiments that follow account for that possible confound by including verbs in present and past tense.

Another result that is derived from the data is that Dutch *seems* to be processed faster as such (main effect of language at the object region). The reason that "seem" is italicized is because this is a result of the particular experiment, as it will be shown in the next Chapter. Actually, the sentences used in Dutch had a strong pronoun in the subject position, contrary to Greek that had a proper name. Recall that according to ACT-R, integrating an item that has an identical feature chunk with one that is already activated (two PNs in the same clause) creates interference, and thus, delay. Interpretation of the object in a Dutch sentence involved only one proper name, the one in object position. In Greek, on the other hand, interpretation of the proper name was delayed due to interference with the proper name of the subject (a chunk with overlapping features), still active in WM, resulting in a seemingly advantage of Dutch. The next chapter will present a follow-up experiment that will balance that factor and, as it will be seen, indeed Greek sentences, due to their higher availability of resources, are,*in total*, processed faster than Dutch (all other factors kept constant of course).

Summing up, as the model predicted, Greek, due to its rich morphology saves on resources and the operations involved in referentially-dependent lexical items in object position are "masked". In order to see whether this is the case, and to overload the computational system in Greek the next experiments will add on the complexity and on the consumed processing resources. The experimental items will become longer with the addition of a second clause. Furthermore, the second clause will contain a pronoun that will refer to the "just-processed" event to test the principle "what is easy to access is hard to re-access". The questions that follow are:

Q8: What modulates the strength of the trace of the representation, in WM, of a "just-processed" event?

Q9: Will the speed of re-addressing a "just-processed" event in memory follow the "easy-to-process-hard-to- re-access" principle?

CHAPTER 5

Memory representation of events

5.1 Storing and re-accessing an event's representation

The experiments presented in this chapter aim to test the second part of the model presented in section 3.6 and the predictions that follow from the assumption regarding the computational system's capacity, at a within- (column 3 in Table 3.4) and a between-language level. More precisely, the first goal is to overload the system that uses few resources during first activation of the verb (as in the case of Greek) and investigate its processing behaviour. Furthermore, the way an event is represented in WM will be explored.[1]

The experimental sentences are the same as the ones in Experiments I & II, presented in Chapter 4, and are supplemented with a second clause that contains a pronoun which refers to the event described in the

[1]It is important to note that I am dealing with event *representations* and not events in the *semantic* sense. For ease of expression and where no misunderstanding arises I will use the term event for both.

first clause (an example is given in (28)).

(28) a. Helen praises Peter *and I find **it** adorable*

b. Helen praises herself *and I find **it** adorable*

The pronoun '*it*' in (28) refers to the 'Helen's-praising-of-Peter' event, in (28a), and to the 'Helen's-self-praising', in (28b). The speed with which the pronoun '*it*' will be processed depends on the strength of the trace that the representation of the event has in WM. Logically, the trace of the representation of an event can be either modulated by the strength of the event's most prominent element, the verb, or by the strength created during the processing of each of the event's constituents. The hypotheses are thus:

H1 The strength of the trace of a "just-processed" event in WM depends only on the trace of its main verb.

H2 The strength of the trace of a "just-processed" event in WM depends on the processing effort consumed for all the items during its processing.

If H1 holds, the pattern expected for the processing of the pronoun is *independent* of whether the object of the first clause is referentially-dependent (reflexive) or not (proper name). Rather, for both conditions, the events that contain a main verb with a weak trace of representation (high Activation Potential) will be re-addressed slower than the events whose main verb has a strong representation trace (low Activation Potential). In information-theoretic terms, the former would correspond to an event with a main verb with high value of Inflectional entropy which will be activated slower than an event containing a verb with low value of Inflectional entropy.

If H2 holds, then processing of the pronoun '*it*' will depend on how the object was processed; it will be condition- and language-dependent. To be more precise, there are two clauses that need to be processed: one that creates an event and another one that contains an element (the pronoun) that needs to re-access the first event to get interpreted. For Dutch, the cases in which the first clause was hard to process are all conditions except for the event of a verb with high InflH and a PN (highInfl-PN). In fact, the events with a verb of low InflH will be hard because the verb was too costly to activate, as a result of its low Activation Potential, and the events with a verb of high InflH and a reflexive (highInfl-Ref) will be hard because they involve re-addressing a weak trace, a process that consumes a lot of resources. As a result, no interaction effect between InflH and Object type is expected for Dutch, at the region of processing the pronoun ‘*it*’.

For Greek, on the other hand, I claimed that the system has so much resources left that even a costly re-addressing of a weak trace is accelerated and “masked”. If that is indeed the case, then an interaction is expected at the pronoun position because processing the second clause will take place in a system that has already used some of its resources (quite like the first stage of Dutch). Whether the predicted no effect for Dutch is a ceiling or floor effect and whether the predicted interaction in Greek will have the same or the reverse direction of that assumed to be “masked” at the object region depends on whether re-addressing of an event falls under the “easy-to-activate-hard-to-re-access” principle (Hypothesis H3 below).

H3 Re-addressing an event follows the “easy-to-activate-hard-to-reaccess” principle.

The predictions that correspond to the hypotheses are:

P5 Processing of the pronoun ‘*it*’ follows the same pattern as processing of the verb.

P6 Processing speed of the pronoun ‘*it*’ is language and condition dependent. An interaction between InflH and Object type is expected for Greek and no interaction is expected for Dutch.

Another issue that will be investigated is the claim I made in the discussion of Section 4.7, namely that proper names were very slow at high values of InflH in the entropy continuum for Greek (analysis presented in Section 4.6.1) in comparison to Dutch, as a result of the different linguistic expressions used in the subject position of each experiment. Recall that the subject position was filled with a proper name in the Greek Experiment II, in contrast to the strong pronoun used in the Dutch Experiment I. I argue that this activated PN for the Greek cases was the one that caused interference with the second PN in the object position resulting in delayed processing times. The second set of experiments does not suffer from such an imbalance. The experimental items are identical in all critical regions and allow a better comparison of the between-languages effects.

5.2 Experiments III (Dutch) & IV (Greek)

The experimental method employed was again a self-paced reading task. The method and equipment are the same as in Experiments I & II and as described in Section 4.2.1.

5.2.1 Experiments III & IV: design & material

Thirteen Dutch and sixteen Greek transitive verbs were used in two conditions; with a referentially-dependent object (reflexive: +d) and with a non-referentially-dependent object (proper name; −d), resulting in twenty-six and thirty-two experimental items for Dutch and Greek, respectively (see Table 5.1).

Table 5.1: Number of experimental items per condition for Dutch and Greek. Each participant saw all the experimental items of the language tested (repeated measures design).

	# items	Object Type	*total*
Dutch	13	2 (+d, −d)	26
Greek	16	2 (+d, −d)	32

An example of the experimental sentences can be seen in (29) for Dutch and (30) for Greek.

(29) Loes helpt, in de meeste gevallen, zichzelf/ Jaco en sinds
Loes helps in the most cases herself/ Jaco and since
kort vind ik dat echt zeer voorbeeldig.
shortly find I that really very exemplary.
'In most cases, Loes helps herself/ Jaco and recently I've been thinking that's very exemplary.'

(30) I Eleni epipliti me kathe efkeria ton eafto tis
the Eleni reprimands with every chance the self hers.CL.GEN
/ton Apostoli ki egho edho ke kero to vrisko
/the Apostolis and I here and time it.CL.ACC find
shedhon aparadhekto.
almost unacceptable.
'Eleni reprimands herself/ Apostolis at every opportunity and, a long time now, I find it almost unacceptable.'

The values of the Inflectional entropy of the verbs ranged from 1.324 to 2.227 bits for Dutch and, for Greek, from 2.403 to 4.730 bits (see Table 5.2). The structure of the experimental items is shown in Table

Table 5.2: Range of inflectional entropies used in experimental items for Dutch and Greek

	min InflH	max InflH	mean InflH
Dutch	1.324 bits	2.227 bits	1.864 bits
Greek	2.403 bits	4.730 bits	3.797 bits
Overall	*1.324* bits	*4.730* bits	*2.881* bits

5.3, for Dutch and Table 5.4, for Greek. The subject position contained a proper name, unique for each item, with the same number of syllables and similar frequency. Four proper names, with similar frequencies, were altered in object position, to balance the fact that the reflexive appeared more than once. They were controlled for length, at the syllable level, with the reflexive (two syllables for Dutch *zichzelf* and five syllables for Greek *ton eafto tou/ tis*, the-self-his/hers: him/herself in Greek). Proper names used in both experiments were half masculine and half feminine.

The critical regions are the point of the verb, the point of the object and the point of the pronoun (regions 2, 7 & 13 for Dutch and regions 2, 6 & 12 for Greek). All the intervening words between the verb and the object (regions 3 to 6 for Dutch and regions 3 to 5 for Greek) and between the object and the pronoun (regions 8 to 12 for Dutch and regions 7 to 11 for Greek) were kept identical, to ensure that the expected processing cost will be constant across items and to capture spillover effects. Words used in the two spillover regions after the pronoun were of the same class and were controlled for number of syllables. Sentences continued after the spillover regions to avoid end of a sentence effect (Abrams and Bever, 1969; Just and Carpenter, 1980).

Two thirds of the total items were fillers sentences of balanced length and complexity that were used as distractors. In order to prevent overusing of present tense, a factor that was possible confound in Experiments I & II, the fillers contained verbs in both present and past tense. Half of the total items were followed by a comprehension statement which the participants had to judge as true or false, given the preceding sentence. Eight items that did not resemble any of the items in the actual task were used as practice to familiarize participants with the self-paced reading task. For the list of the verbs used and the corresponding InflH values see Appendix A.

Table 5.3: Structure of experimental items for Experiment III in Dutch. Critical regions are marked in bold.

Loes VERB *in most cases* OBJECT *and lately I find* IT *very Adj*							
region	1	**2**	3 to 6	**7**	8 to 12	**13**	14 15
+d: R −d: PN	Loes	**verb**	in de meeste gefallen	**zichzelf** **Jaco**	en sinds kort vind ik	**dat**	echt seer Adj
InflH		varying	constant		constant		contr.

Table 5.4: Structure of experimental items for Experiment IV in Greek. Critical regions are marked in bold.

Helen VERB, *in every opportunity,* OBJECT *and I lately find* IT *very Adj*							
region	1	**2**	3 to 5	**6**	7 to 11	**12**	13 to 16
+d: R	I Eleni **verb**		me kathe efkeria	**ton eafto tis**	ki ego edo ke kero	**to**	vrisko ligo Adj
−d: PN				**ton Apostoli**			
InflH		var.	const.		const.		contr.

The predictions specific to the experiment are:

P7 The pronoun '*it*' will be processed in accordance to the trace of the verb *only*. As such, it will be processed slower when referring to an event description containing a verb with high values of InflH (because the highInflH verbs have weak representations) than when containing a verb with low InflH (because the lowInflH verbs have strong representations).

P8 No effect at the region of the pronoun is expected for Dutch, as a result of "ceiling" performance in accessing representations of events that have strong traces because a lot of resources were consumed during their processing. For Greek, events with high InflH verbs are expected to be processed overall faster but for different reasons: the reflexive ones because they have a very strong trace (a lot of resources were consumed during the re-addressing of a highInflH weak trace resulting in a strong event trace) and the PN ones because they will be accelerated by the resources (they consumed the least resources, as their processing induced effort only for the introduction of the PN, a process that appears not to be costly when the resources suffice).

5.2.2 Participants

Forty-five Dutch students (twelve of them male) of Utrecht University and forty-five Greek students (twelve of them male) of the University of

Athens were paid to participate in the experiment. The Dutch students were 18 to 30 years old and the Greek 21 to 29 years old. They were all native speakers of Dutch for the Dutch experiment and Greek for the Greek experiment and were naive as to the purpose of the study. None of them had participated in Experiment I or II. The Dutch participants completed the experiment in a soundproof booth at the lab facilities of Utrecht institute of Linguistics OTS. Greek participants were tested on a 13-inch Toshiba laptop screen in a quiet room of the University of Athens. They all completed the task in one session in maximum 25 minutes.

5.2.3 Method of data analyses

Subjects that failed to reach an 85% threshold of correct responses to the comprehension statements were removed from the analyses. This resulted in forty-one remaining participants for the Dutch and forty-two for the Greek experiment. Data for one item in Greek were lost due to a technical problem so the analyses are over fifteen items.

Reading times (RTs) for each word were obtained. Unrealistic RTs, below 100 ms and above 2500 ms, were removed from the analyses. A two-stage residualization approach (Jaeger, 2008; Hofmeister, 2011) was used for the remaining RTs, at each word region, using LMER models in R (Baayen et al., 2008).[2][3] In the first stage ensures that variance due to extra-experimentally defined factors that are known to affect reading times, such as word length (in characters), word position in the sentence and item's position in the list, will be accounted for, across *all* items (both experimental and filler sentences). As such, log-transformed RTs of , were first regressed against the word's length in characters, word's position in the sentence and the log-transformed item's position in the

[2] The method used for the analyses of the data in both Experiments III & IV was the same (and different than the one performed in the first set of Experiments I&II) and will be, therefore, explained once.

[3] I would like to specially thank Alex B. Fine for step by step guidance and help through the analyses.

task, with a maximal random term for participant. The *residuals* of that model, of the experimental items only, served as the dependent variable for the second stage and were crossed with InflH and Object type (with and without a dependency) with maximal random slopes for item and participant. This method enables us to observe any influence of the InflH and Object type that pertains over-and-above the known, just mentioned effects and furthermore to compare the two languages in a fine and clean way. For example, Greek has overall longer words which will be registered as a higher raw RT than a corresponding RT in Dutch, which however will not necesserily reflect a harder process, a pitfall that is accounted for with this residualization.

Results will be presented per region, including the critical and the spillover regions of verb and object, and per language (Dutch *only* and Greek *only*).

5.2.4 Results of Experiment III (Dutch)

The results for Dutch for the first clause are very similar to the first experiment (Experiment I).

Verb

Region 2: region of the verb.
The effect of InflH on reading times did not reach significance.

Region 3: 1^{st} spillover region after the verb.
The effect of Inflectional entropy on RTs was marginally significant ($\beta = -.05, SE = .03, t = -1.758, p < 0.9$) and appeared in the spillover region of the verb (reg 3).[4] Verbs with higher Inflectional entropy yielded faster reading times than verbs with lower Inflectional entropy (Figure 5.1).

Object

[4]As mentioned before, Repeated measures ANOVA for these data gave very significant results. I believe however that the residualization method is more accurate and therefore is the one that is presented here.

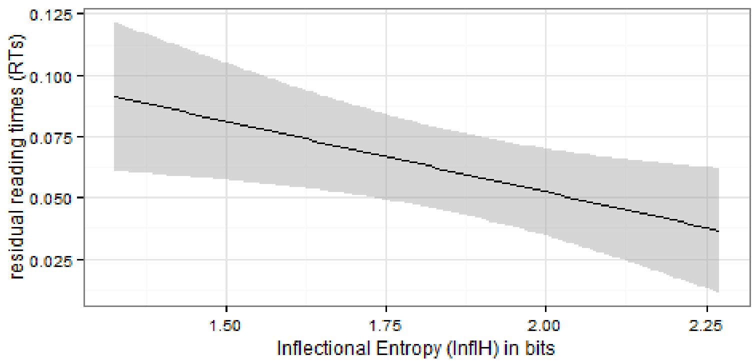


Figure 5.1: (Dutch) FIRST SPILLOVER REGION AFTER THE VERB
Verbs with high Inflectional entropy (high AP) are activated faster. Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to RTs.

Region 7: region of the object.
There main effect of Object type in the region of the object was highly significant ($\beta = -.04, SE = .01, t = -4.194, p = 0$). Reflexives were read faster than proper names. Additionally, a reliable interaction effect ($\beta = .05, SE = .03, t = 2.038, p < .05$) between Inflectional entropy and Object type attests that in higher values of InflH the RTs for proper names are significantly facilitated and the RTs for the reflexives are delayed. The data are plotted in Figure 5.2.

Region 8: 1^{st} spillover region after the object.
A main effect of Object type indicated the faster processing of reflexives for all InflH values ($\beta = -.03, SE = .01, t = -3.586, p < .01$), as seen in Figure 5.3.

Pronoun
Reg 13 & 14: pronoun region and one region after.
There was no main effect or interaction of either InflH or Object type attested as seen in Figures 5.4 and 5.5. This lack of effect is predicted

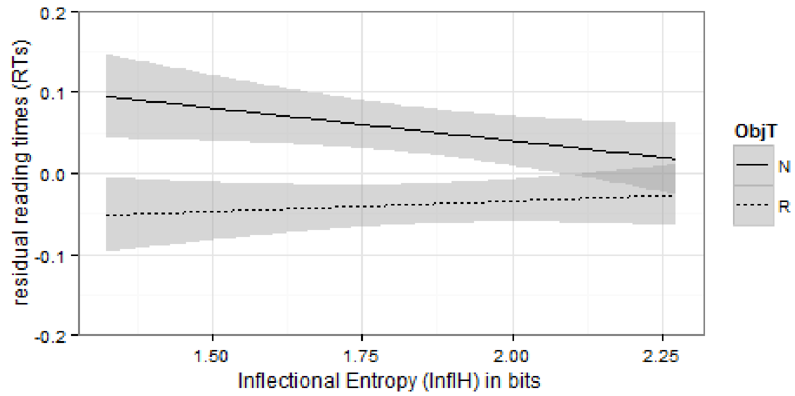


Figure 5.2: (Dutch) Object region
When the values of InflH increase RTs for reflexives get significantly slower whereas RTs for proper names get significantly faster. This effect indicates the additional processing effort exerted during re-addressing a weak trace of a high InflH verb for the interpretation of the reflexive. Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the residual RTs for each Object type condition ('N'= proper name and 'R'=reflexive).

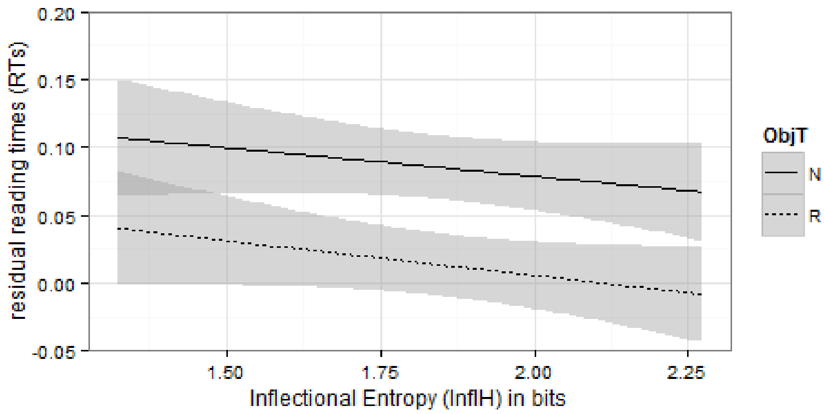


Figure 5.3: (Dutch) First spillover region after the object
Reflexives are processed overall faster than proper names. Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the residual RTs for each Object type condition ('N'= proper name and 'R'=reflexive).

by the model and reflects a "ceiling" performance: the representations of the events are very easy to access because they have very strong traces (for independent reasons, as already discussed).

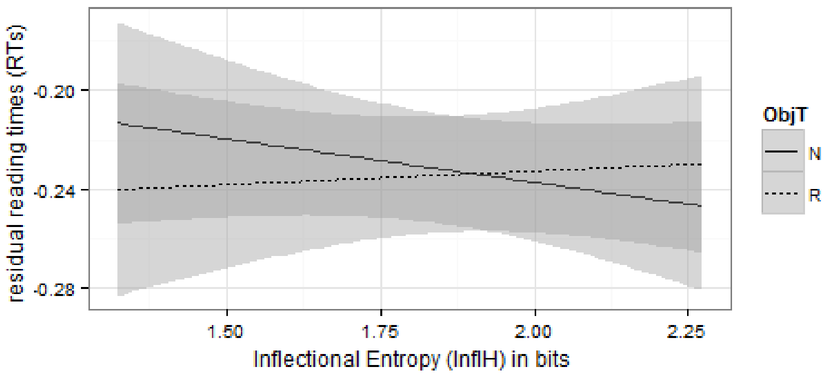


Figure 5.4: (Dutch) PRONOUN REGION
No interactions or main effects between Inflectional entropy and Object type ('N'= proper name, 'R'=reflexive) on reading times reach significance at the region of the pronoun.

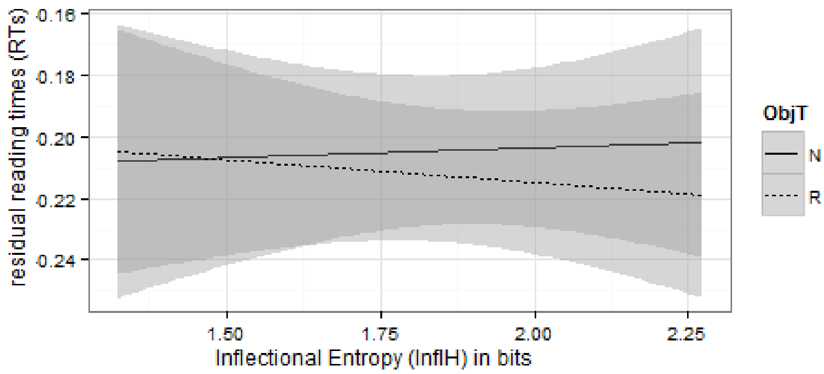


Figure 5.5: (Dutch) FIRST SPILLOVER REGION AFTER THE PRONOUN
No interactions or main effects between Inflectional entropy and Object type ('N'= proper name, 'R'=reflexive) on reading times reach significance at the first spillover region after the pronoun.

Region 15: 2^{nd} spillover region after the pronoun.
A reliable interaction of Inflectional entropy and Object type is attested at the second spillover region after the pronoun ($\beta = .07, SE = .02, t = 3.300, p < .001$). The pronoun *dat* is read slower when referring to a low entropy proper name event than when it refers to a low entropy reflexive event. High entropy delays reflexives and accelerates proper names (Figure 5.6). The direction of the effect is similar to the one observed at the point of the object only in this region, in contrast to the object region, the simple slope is more significant for the reflexive ($\beta = .09, SE = .04, t = 2.333, p < .03$).

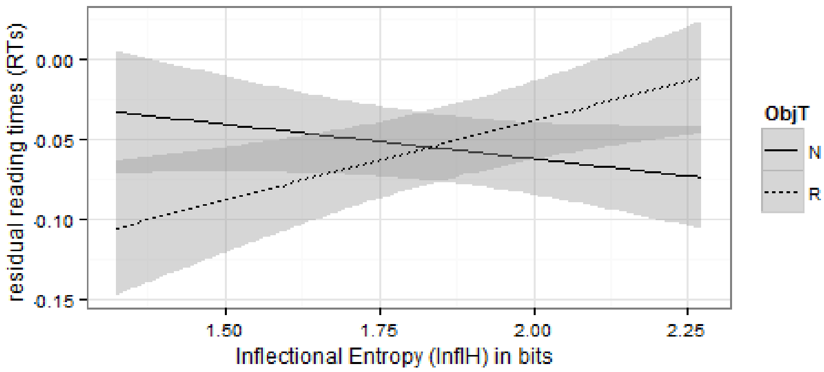


Figure 5.6: (Dutch) SECOND SPILLOVER REGION AFTER THE PRONOUN
Reading times for events that contain a reflexive are delayed in the higher values of Inflectional entropy (high AP). Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the residual RTs for each Object type condition ('N'= proper name and 'R'=reflexive).

5.2.5 Summary of Experiment III (Dutch)

The second experiment in Dutch replicated the findings of Experiment I for the verb activation (reg 3) and the processing of the object (reg 7). In fact, the effect at the object position in this experiment is stronger than the one observed in Experiment I and shows more clearly the two different processes involved in referentially dependent versus referentially independent lexical expression. The statistical analyses of these data took into consideration most known factors that affect reading and therefore gave a better insight into the data.

Re-accessing the event through the pronoun '*it*' gives rise to no interaction or main effect. This is a result of the strong traces that the representations of the events have in both conditions, due to the effort consumed during their processing. The observed results support H2: the strength of the trace of a "just-processed" event in WM depends on the processing effort consumed for all the items during its processing.

For the second spillover region, it is not clear which processes it mirrors. A suggestion could be that the available processing resources are so few that effects become now discernible, in the sense that when resources abound, operations can be masked, whereas when resources are few, it is easier to detect what causes trouble and what not.

5.2.6 Results of Experiment IV (Greek)

The results of the Greek Experiment IV for the first clause are very similar to the ones observed in the Greek Experiment II.

Verb

Region 2: region of the verb.

A strong facilitation effect of Inflectional entropy on reading times ($\beta = -.03, SE = -.01, t = -2.477, p < .05$) was attested at the region of the verb as seen in Figure 5.7.

Object

Region 6: region of the object.

There was no main effect or interaction Inflectional entropy and Object type at the region of the object.

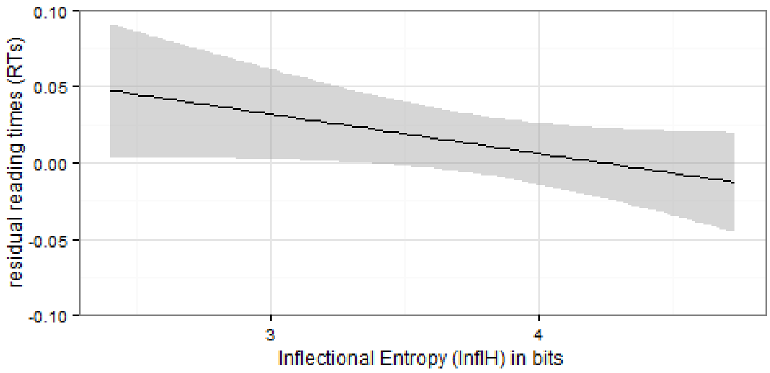


Figure 5.7: (Greek) VERB REGION
High values of Inflectional entropy (high AP) reliably facilitate the activation of the verb. Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the residual RTs.

Region 7: 1^{st} spillover region of the object.
A main effect of object type ($\beta = -.02, SE = .01, t = -2.3, p < .05$) attests the faster RTs for the cases with the reflexive as seen in Figure 5.8. The interaction between Object type and InflH did not reach significance.

Pronoun

Region 12: region of the pronoun.
There were no main effects or interactions of InflH and Object Type on reading times attested, at the region of the pronoun.

Region 13: 1^{st} spillover region of the pronoun.
A main effect of InflH ($\beta = -.03, SE = .0009, t = -3.073, t < .01$) one region after the pronoun is attested. Reading times for both Object type conditions become faster when the values of Inflectional entropy increases, as seen in Figure 5.9.

Region 14: 2^{nd} spillover region of the pronoun.
A main effect of object type two words after the pronoun significantly

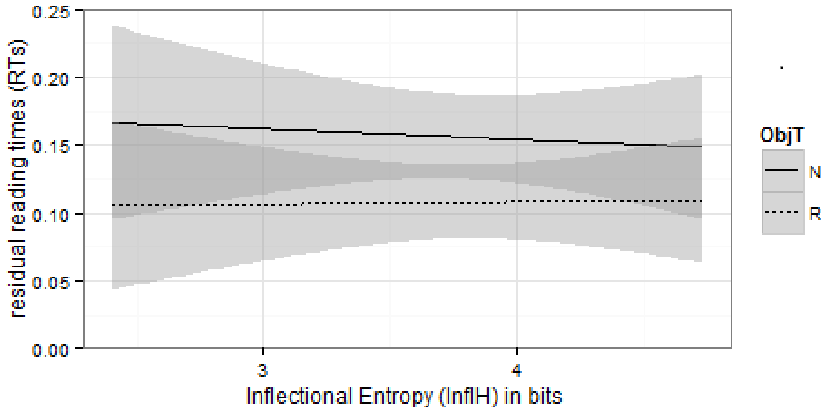


Figure 5.8: (Greek) First spillover region after the object
Reflexives are processed significantly faster one region after the object. Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the residual RTs for each Object type condition ('N'= proper name and 'R'=reflexive).

delays reading times in the reflexive condition ($\beta = .027, SE = .008, t = 3.467, p < .001$). Additionally, and similar to Dutch, there is a significant interaction between Object type and Inflectional entropy on reading times ($\beta = -.022, SE = .0095, t = -2.366, p < .05$). RTs in the reflexive condition become faster when the value of InflH increases whereas there is no such relation attested for the RTs in the condition with the proper name. the data are plotted in Figure 5.10.

5.2.7 Summary of Experiment IV (Greek)

For the verb and object region the results replicate the findings from Experiment II. Processing of verbs is facilitated in the higher values of InflH. The effect indicates, once more, that the Activation Potential of a verb is proportional to the value of the Inflectional entropy of the verb's paradigm. Furthermore, reflexives are processed faster than proper names. As with Experiment II, the lack of an interaction between InflH

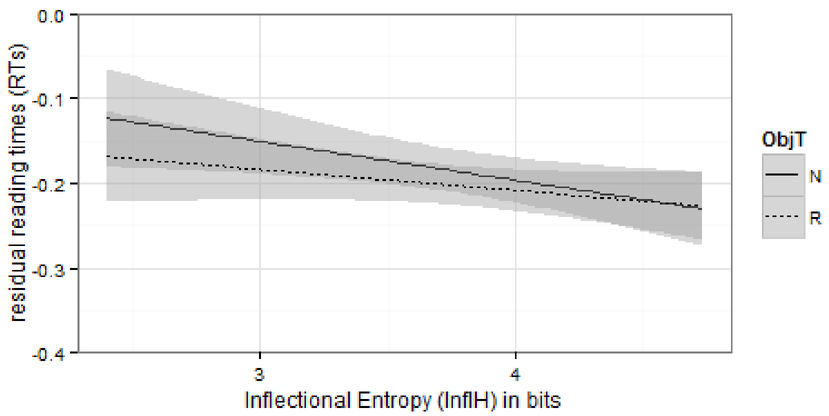


Figure 5.9: (Greek) First spillover region after the pronoun Higher values of InflH facilitate RTs in both conditions, one region after the pronoun. Events that contain verbs of high Inflectional entropy (and high AP) are re-accessed faster than events that contain verbs with low value of InflH (and have thus low AP). Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the residual RTs for each Object type condition ('N'= proper name and 'R'=reflexive).

and Object type at the object- and the spillover-regions is assumed to be an effect of the abundance of processing resources. More precisely, I take this absence of an interaction to be a case of "masking" through the acceleration of the processing resources and the lack of such a sensitivity of the task, an assumption that is supported by the main effect of Inflectional entropy at the pronoun region. Additionally, processing of the reflexive as an object of a verb with a weak trace (highInflH-Ref) did create a strong trace of representation of the event which in turns accelerated its re-accessing when needed for the interpretation of the pronoun '*it*'.

5.2.8 Summary of results of Experiments III & IV

The experimental items in this second set of experiments were identical and the residualization method that was used to analyse the data

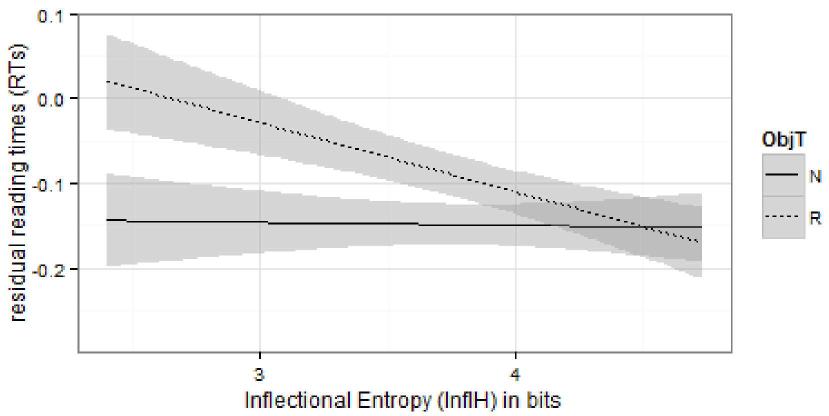


Figure 5.10: (Greek) SECOND SPILLOVER REGION AFTER THE PRONOUN Reading times in the reflexive condition are overall slower than the RTs in the condition with the proper name. However, processing of reflexives is facilitated when the values of Inflectional entropy increase. Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the residual RTs for each Object type condition ('N'= proper name and 'R'=reflexive).

removed most of the factors (at least the ones that are widely known) that influence processing speed, enabling attributing the observed effects to the influence of the InflH. So, the data from Experiments III & IV replicate, in the first clause, the findings from Experiment I& II of the previous chapter but the effects are stronger. Even more, the contribution of the insertion of a second clause showed that re-accessing a "just-processed-event" is influenced by the trace that this event has in WM and the state that the system is found in at that processing step, in terms of available processing resources. Re-accessing an event representation that is stored in WM is dependent on whether it is a "self"- or a "PN"- event, supporting H2: the strength of the trace of an event representation depends on the processing effort consumed during processing all the items that constitue the event. For the overloaded system in the Dutch cases it holds that the traces of the events are strong, either because of re-addressing or because of high consumption of resources, resulting in an overall fast re-accessing of the event representation. For Greek, on the other hand, both Object type conditions are faster when the events contain a high InflH verb because of the strong trace after re-addressing (in the self-event cases) and because of the high availability of resources (in the PN-event cases). The facilitation of the highInflH-Ref cases for Greek supports H3: re-accessing a stored event falls under the "easy-to-access-hard-to-address" principle.

5.3 Analyses of the collapsed data

To investigate the way a representation of an event is re-accessed independent of language, the data were collapsed together in one merged dataset. The same residualization process was used as in the individual analyses, but this time over the merged dataset. The results are similar but because the range of the values of InflH is larger such an analysis can give a clearer insight into the time course of processing a sentence like (28).

Results will be presented per region of interest. Regions were recoded for the analyses because of the difference in the position of the critical region in the two experiments in each language. Hence, *Obj* corresponds to region 7 for Dutch and 6 for Greek, and *Pron* corresponds to region 13 for Dutch and 12 for Greek.

Verb

Region 2: Verb region

There was a main facilitatory effect ($\beta = -.023, SE = .008, t = -2.759, t < .01$) of Inflectional entropy on RTs, seen in Figure 5.11.

Object

Region Obj: object region 7 for Dutch and region 6 for Greek.

Main effects and interactions were observed. RTs get significantly faster as the value of InflH increases (main effect of InflH: $\beta = -.031, SE = .01, t = -2.947, p < .01$). Furthermore, a main effect of Object type

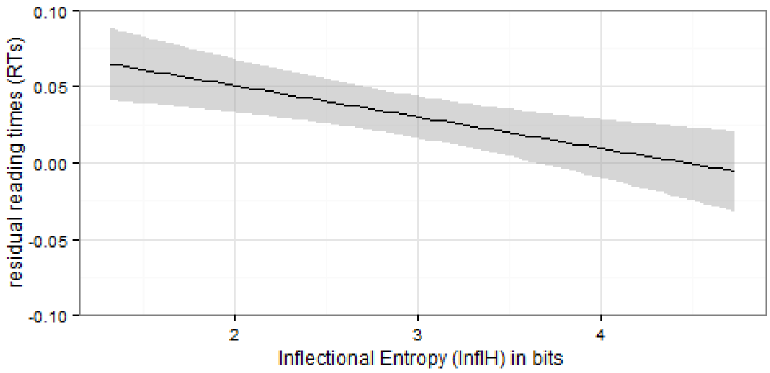


Figure 5.11: (Collapsed data) VERB REGION
Residual RTs of the verb get significantly faster in the higher values of InflH. High InflH increase the Activation Potential of the verb and facilitates its activation. Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the residual RTs.

($\beta = -.02, SE = .008, t = -2.499, p < .05$) attests that reflexives are processed overall faster than proper names. The interaction between InflH and Object type was also reliable ($\beta = .015, SE = .006, t = 2.384, p < .01$). As seen from the plotted data in Figure 5.12, the main effect of Object type is an artefact. Proper names are read slower than reflexives in the lower values of entropy. For higher values of entropy, reflexives are read marginally slower and proper names marginally faster. The results confirm the predictions of the model described in Section 3.6.

Pronoun

Region Pron: pronoun region 13 for Dutch and region 12 for Greek.
There was a significant main effect of Inflectional entropy on reading times ($\beta = .017, SE = .008, t = 2.241, p < .05$). RTs at the pronoun region become slower, for both conditions, in the higher values of InflH (Figure 5.13). The reverse direction of the slope, as compared to the object region (Figure 5.12), suggests that re-accessing an event representation also follows the “easy to process, hard to re-access” principle.

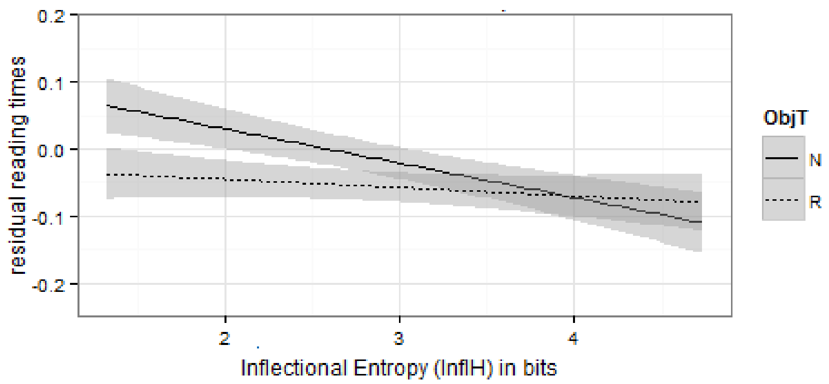


Figure 5.12: (Collapsed data) Object region
Main effects and interaction of InflH and Object type at the object region. Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the residual RTs for each Object type condition ('N'= proper name and 'R'=reflexive).

5.3.1 Summary of the analyses of the collapsed data

When the data are collapsed it makes little sense to think about the results of the individual experiments because these data were treated, in the analyses, as coming from one experiment. The residualization technique was used to take into consideration all the factors (that are known to influence RTs at least) that were specific to the languages under study and remove any of the variances explained by them. The analyses indicate how the computational system behaves depending on the effort consumed at each stage of processing. So, the main conclusion derived from the analyses is that the "easy-to-activate-hard-to-re-access" principle acts at each point of a sentence that this principle would apply, namely at the reflexive object position and at the pronoun position. This conclusion is clear from the graphs (note the different direction of the slopes) and justified by the statistical analyses.

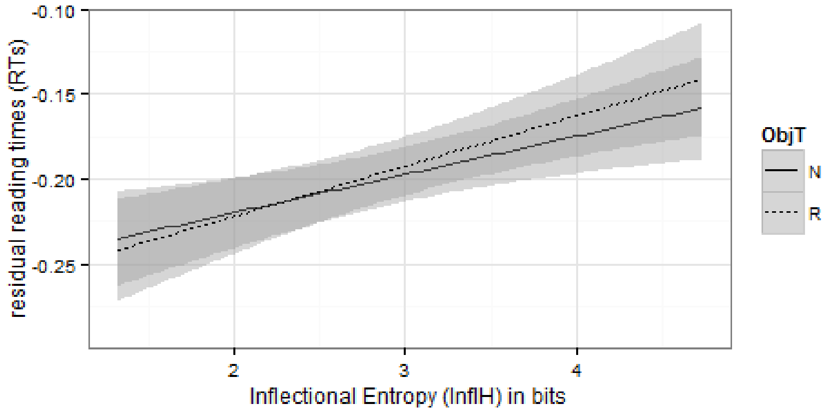


Figure 5.13: (Collapsed data) PRONOUN REGION
Processing speed of the pronoun becomes slower as the InflH increases suggesting that re-accessing events that were fast to process is harder than re-accessing events that were processed hard. Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the residual RTs for each Object type condition ('N'= proper name and 'R'=reflexive).

5.4 Between languages

The analyses between languages were performed using LMER on residual RTs *per language* that were further crossed with language and object type. The reason for these analyses is to investigate the way that different types of sentences are processed between languages.

Verb

Region Vb

A significant main effect of language was observed ($\beta = -.02, SE = .01, t = -1.981, p < .05$). Greek RTs were significantly lower than RTs for Dutch at the region of the verb. This effect was expected due to the higher values of Inflectional entropy of Greek verbs and has already been attested in all the analyses (Figure 5.14).

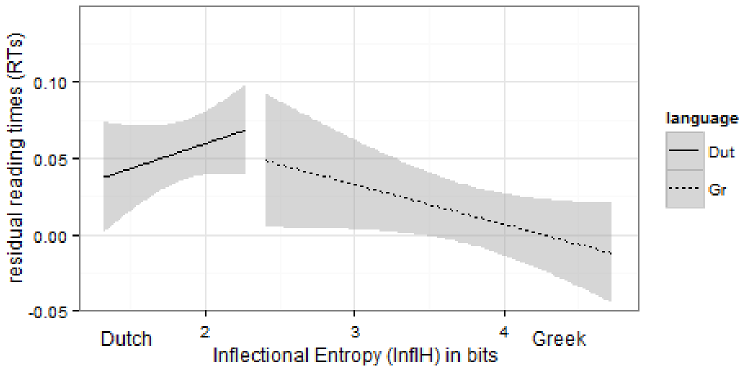


Figure 5.14: (Between languages) VERB REGION
Reading times for Greek are lower than reading times for Dutch at the object region, suggesting faster activation of the verbs in Greek as a result of their higher values of InflH. The fact that the regression line for Dutch goes up reflects the observation in the individual analyses, in which the effect of InflH for Dutch appeared in the spillover region of the verb.

Object

Region Obj

Main effects and interactions were attested at the object region. A main effect of language ($\beta = -.061, SE = -.028, t = -2.25, p < .05$). Reflexives are also processed overall faster ($\beta = -.041, SE = .027, t = -2.443, p < .05$).attests that residual RTs for Greek were significantly lower than RTs for Dutch at the object region. An interaction between Language and Object type ($\beta = -.044, SE = .016, t = -2.703, p < .01$) attests that Dutch proper names are read slower than Greek ones. This is the effect of the availability of resources for the Greek sentences due to the little effort spent during activation of the verb. Data are plotted in Figure 5.15.

Pronoun

Region Pron

A main effect of Language and an interactions between Language and

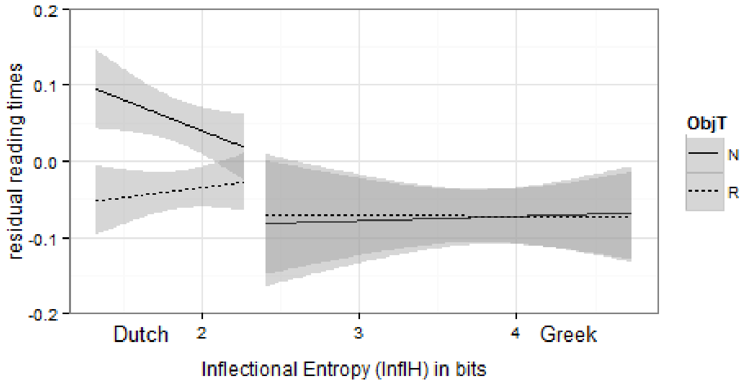


Figure 5.15: (Between languages) Object region
Greek is processed overall faster as seen by the lower residual times. Dutch proper names are processed slower than Greek proper names. Processing of reflexives in Dutch becomes harder in the higher values of InflH (for Dutch verbs). Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the residual RTs for each Object type condition ('N'= proper name and 'R'=reflexive).

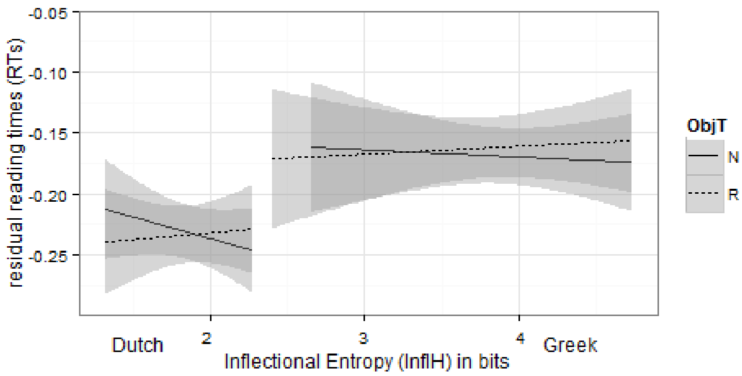


Figure 5.16: (Between languages) Pronoun region
Processing of the pronoun in Greek is slower than in Dutch. Dutch events have weak traces of representation, due to their fast processing at the object region, resulting in slower re-accessing when required for the interpretation of the pronoun. Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the residual RTs for each Object type condition ('N'= proper name and 'R'=reflexive).

Object type were attested at the region of the pronoun. Greek is now processed significantly slower than Dutch ($\beta = .065, SE = .025, t = 2.583, p < .01$). Re-accessing an event follows the "easy-to-activate-hard-to-re-access" principle.

5.4.1 Summary of between-language analyses

The data from the between-language analyses support the predictions of the model regarding the trade-off between resources and processing cost. From these analyses, one can see how a system that processes poor morphology, like Dutch, might be slow while processing the first clause, but accelerates during the second clause. Dutch verbs are costly to activate resulting in a slower object integration and interpretation, but they compensate for that by storing a stronger representation of the event. Consequently, when the event needs to be re-accessed for the interpretation of the pronoun, Dutch events are processed faster than Greek, for which holds exactly the opposite.

5.5 Discussion

This chapter investigated the way that "just-processed" events are represented in WM and how they are, in turn, re-accessed when needed for the interpretation of a pronoun like '*it*'. The strength that an event will have in WM is determined by the way that the event was processed and again, two factors are traded off: the strength of the trace of the main verb along with the requirements of the object against the amount of available resources that system has. Because strong verb traces mean that there have been a lot of resources already consumed and, at the same time, re-accessing a verb with a weak trace also requires processing that strengthens its trace, we can talk about, roughly, 3 degrees of trace strengths of events: weak, mild and strong. The fact that there is no effect at the pronoun region, or the first spillover in Dutch, points to a ceiling effect for Dutch. Having spent a lot of resources in the first activation of the items and the processing of the first clause, all the relevant traces are strong enough to be processed equally fast. This is similar to what happens in Greek at the object position and in accordance with the hypothesis in the beginning of the chapter.

Re-accessing event representations in Greek, on the other hand, follows the same line of argumentation and, as expected, the fast processing in the first clause will induce delays while processing the second clause. The delays will be relative to the strength of the trace of representation of the event. Three types of strength of traces can be identified: weak, strong and mild.

Weak traces are traces of the events that contain a verb with a weak trace and a proper name in the object position (which corresponds to the highInflH-PN condition). Those events are hard to re-access.

Strong traces are traces of the events that contain a verb with a strong trace and a reflexive in the object position (that corresponds to the LowInflH-Ref condition). Also the events that consist of a verb with a strong trace and a PN will have a strong trace. These events are re-accessed fast.

The mild traces are traces of the events that contain a verb that has a weak trace and a reflexive in the object position (highInflH-Ref condition). The trace has become mild because of its re-addressing for the interpretation of the reflexive, which for this condition is particularly hard and strengthens the trace. It is not very clear a priori, if the trace is strengthened enough for the event to pattern with the highInflH-PN condition, because the particular experimental task can give no insight on the exact amount of resources spent. That is, it is not, a priori, clear, what is more powerful: the strengthening of a trace through the processing effort imposed on it, or the resulting shortage in resources? As Figure 5.9 shows, and the statistics justify, the highInflH-Ref condition patterns with the highInfH-PN condition indicating that re-addressing a very weak trace uses a lot of resources and makes the event's trace sufficiently strong to be re-accessed faster.

Coming back to the Hypotheses posed in the beginning of the chapter, the data justify P6 and H2 is borne out: the strength of the trace of a "just-processed" event in WM depends on the processing effort consumed for all the items during its processing. The fact that events that were processed slower were re-accessed faster (results of the collapsed data, presented in Section 5.3) supports H3: re-addressing an event follows the "easy-to-activate-hard-to-retrieve" principle . So,

- The activation level of an event depends on the processing effort consumed for all the items during its processing.
- Re-addressing a very weak trace requires a lot of resources that suffice to make the trace strong enough to be-addressed faster.
- Re-addressing an event follows the "easy-to-activate-hard-to-re-access" principle.
- Events that were hard to activate are easy to re-access at a *within* and a *between* language level.

What happens when the computational system is not yet fully developed as may be the case in, for instance, children? It is known that children in development do not process language in an adult-like way and this has been often attributed to their limited processing capacity (Grodzinsky and Reinhart, 1993, among others). Studies focused mainly on processing of structures with high syntactic complexity or various degrees of ungrammaticality. Is this processing capacity so limited as to make children process grammatical sentences with easy structure slower than adults? The following chapter will address this point with the same experiment presented in the present one, conducted with children.

CHAPTER 6

Resources and representational traces in development

6.1 Processing in children

Children have been shown to process language in a non-adult way and this has been also attributed to a "limited processing capacity" either in the sense that the computations are too hard to master (Grodzinsky and Reinhart, 1993, a.o.) or that the allocation of attention is not yet developed (Trueswell et al., 1999, a.o.). Note that "limited processing capacity" could either refer to the insufficient amount of *resources*, or to an *under-developed* computational system. The former refers to a fully functioning (and developed) processing system, that is not capable, in terms of resources, to process a high load of material whereas the latter describes a system in which not all processes are fully mastered, although the amount of resources are there (see Leonard et al., 2007, for similar considerations).

The structures that I have been looking at so far induce, in spite of their simple nature, processing delays, even in adults, due to the differences in the strength of the traces of the representations stored in WM (combination of lexical properties, like the Activation Potential, and linguistic requirements, such as building a dependency) and the state of the system's processing resources after first activation of the verb. The present chapter investigates whether children process structurally fairly easy sentences, like the ones used in the second set of experiments (Experiments III & IV), in a different manner than adults. Recall that the speed of sentence comprehension is described through the relationships seen in (31), as already introduced in Section 3.6. Furthermore, the capacity of the system is subject to the principle expressed in (32).

(31) Sentence comprehension ($n = 0$)

a. Information theoretic quantification of Activation Potential of a verb i belonging to a paradigm p in LTM:

$$AP_i = X + \mathit{InflH}_p = X + \left(-\sum_{j=1}^{c} \frac{\frac{F_j}{R_j}}{\sum_{j=1}^{c} \frac{F_j}{R_j}} \times \log_2 \frac{\frac{F_j}{R_j}}{\sum_{j=1}^{c} \frac{F_j}{R_j}}\right)$$

b. Strength of the trace of an activated item $= \dfrac{k}{AP_i} = \dfrac{k}{\mathit{InflH}_p}$

c. Total activation of a verb in WM:

$$A_i = \ln\left(\sum_{j=1}^{n} t_j^{-d}\right) + \frac{k}{InflH_p} + \sum_j W_j S_{ji}$$

(32) The state at which $R(esources)_{L(eft)} = \dfrac{avail. - cons.}{avail}$ res. $\rightarrow 0$ can slow down computations,

The fact that children process language in a different way than adults, can be due to several factors, some of them are: i) the children's processing *capacity* is smaller than that of the adults, ii) children process linguistic material with a lower *speed* than adults (they have a lower

k), iii) the children's lexical organization has *weaker* connections than the lexicon of the adults (they have lower values of AP). The emerging hypotheses are thus:

H4 Children in development have lower processing *capacity* and they come at the stage of a shortage in resources faster than the adults.
$R_{Lchildren} \rightarrow 0$ faster than $R_{Ladults} \rightarrow 0$

H5 Children in development process with a lower *speed* than adults do. From (31b) it follows that the strength of the representations' traces in WM are weaker than that of adults. This would be relevant for the point of re-addressing of the verb and re-accessing of an event.
$k_{children} < k_{adults}$

H6 Children's mental lexicon is not fully developed and the connections within the paradigms are not as strong as in adults. The InflH of the paradigms would have thus lower values.
$InflH_{children} < InflH_{adults} \Rightarrow AP_{children} < AP_{adults}$

The experiment was, therefore, chosen to be conducted in Greek because of the high AP of Greek verbs that would allow a detection of any effects related to the hypothesis H4. After all, lowering down the processing capacity for Dutch might lead, for the particular method used at least, to "floor" effects of too slow processing. The predictions that follow are:

P9 Greek speaking children will behave like Dutch adults, since their system will have reached a higher level of consumed resources after the first activation than that of Greek speaking adults.

P10 Re-addressing representations in WM will be overall hard because of the weak traces.

P11 Lower values of InflH would lead to overall stronger traces in WM (the traces in the system will be similar to that of Dutch after the first activation of the verb) but with as much resources as the system in Greek has, after the first activation of the verb.

6.2 Experiment V in children (Greek)

6.2.1 Experiment V: Design

Twelve Greek transitive verbs were used in two conditions, with and without a referentially dependent item in the object position, resulting in twenty-four items. The value of their inflectional entropies ranged from 2.403 to 5.998 bits (mean 4.031). Each verb was used in two conditions; with a referentially-dependent object (reflexive, +d) and with a non-referentially-dependent object (proper name, -d), resulting in twenty-four experimental items.

The structure of the experimental items was the same as in Experiment IV, repeated in Table 6.1. The subject position contained a proper name, unique for each item, with the same number of syllables and similar frequency. 4 proper names were altered in object position, to balance the fact that the reflexive appeared more than once, with similar frequencies. Furthermore, they were controlled for length, at the syllable level, with the reflexive (5 syllables for Greek *ton eafto tou/ tis*). All proper names used in experiments were half masculine and half feminine.

The critical regions are the point of the verb, the point of the object and the point of the pronoun (regions 2, 7, & 13 for Dutch and regions 2, 6 & 12 for Greek). All the intervening words between the verb and the object (reg 3 to 6, for Dutch and 3 to 5, for Greek) and between the object and the pronoun (regions 8 to 12, for Dutch and regions 7 to 11, for Greek) were kept identical, to ensure that the expected processing cost will be constant across items and to capture spillover effects. Words used in the two spillover regions after the pronoun were of the same class and were controlled for number of syllables. Sentences continued after the spill over regions to avoid end of a sentence effect Abrams and

Bever (1969); Just and Carpenter (1980). For the list of the verbs used and the corresponding InflH values see Appendix A.

Table 6.1: Structure of experimental items for Experiment IV in Greek. Critical regions are marked in bold.

<table>
<tr><th colspan="8">Helen VERB, in every chance, OBJECT and I lately find IT very Adj</th></tr>
<tr><td>region</td><td>1</td><td>2</td><td>3 to 5</td><td>6</td><td>7 to 11</td><td>12</td><td>13 to 16</td></tr>
<tr><td>+d: R</td><td rowspan="2">I Eleni</td><td rowspan="2">verb</td><td rowspan="2">me kathe efkeria</td><td>ton eafto tis</td><td rowspan="2">ki ego edo ke kero</td><td rowspan="2">to</td><td rowspan="2">vrisko ligo Adj</td></tr>
<tr><td>−d: PN</td><td>ton Apostoli</td></tr>
<tr><td>InflH</td><td></td><td>var.</td><td>const.</td><td></td><td>const.</td><td></td><td>contr.</td></tr>
</table>

Forty-six filler sentences of similar complexity and length were used as distractors. Thirty five of the total seventy items were followed by a comprehension statement in which the participants had to judge it as true or false, given the preceding sentence.

Before the actual experiment several sentences were reviewed by five independent teachers and were judged for their applicability for that age (some words used in the previous experiments were judged as too hard for children to understand). Only applicable items were used in the experiment.

The number of items used in this experiment is much smaller than that used for the adults because during the pilot children showed inability to cope with such a large number of items. The option of conducting the experiment in two sessions was rejected in order to be able to compare their performance with that of the adults. Eight items that did not resemble any of the items in the actual task were used as practice to familiarize participants with the self-paced reading task.

The predictions related to the specific structures and relative to Hypotheses H4, H5 and H6 are:

P12 *lower processing capacity* → Slow to floor effect at the object region because of the shortage of resources. A (weak) interaction between InflH and Object type is expected at the object region. A ceiling effect of overall fast processing is expected at the processing of the pronoun.

P13 *weak representational traces in WM* → Reflexives (main effect of Object type) are expected to be overall harder than Proper names at the object region.

P14 *weaker connections in WM* → Floor effect at the verb region which would lead to main effect of reflexives at the object region. Re-accessing an event is expected to be boosted due to amount of resources as in Greek adults.

6.2.2 Participants

Twenty-nine children, four of them male, aged 6;2 to 7; 7 (years; months, mean age: 7; 2) were recruited from the Summer Camp Asimakopoulos in Afidnai with the consent of their parents. Only the ones that wanted by themselves to participate in the experiment did, to avoid excessive boredom effects. All were native speakers of Greek and were naive as to the purpose of the study. They were tested on a 13-inch Toshiba laptop in a quiet room at the Camp facilities and completed the task in a maximum 45-minute session each. Children were advised to ask for a break whenever they feel tired but after have finished the sentence they were reading.

6.2.3 Experiment V: Data analyses

Three children were removed from the beginning because they failed to complete the task. Five more children that didn't pass the 80% threshold in correct answers to the comprehension questions were further removed from the analyses. This resulted in 21 children, the reading times of which were included in the analyses. One experimental item had to be removed from the analysis because of lost reading times due to a technical mistake in the script.

Unrealistic reading times (RTs), below 100 ms and above 2500 ms, and observations that were three standard deviations above or below item and subject mean for each position were excluded from the analysis ($< 1\%$ of the observations).

RTs in each word were log-transformed to approximate normality and were analysed with LMER analyses using the 2-stage model. RTs, in each region, were regressed in a maximal random analysis against crossed InflH and Object type (with and without a dependency) with random slopes and intercepts for item and participant. A logarithmic-transformed term for the position of the item in the task was included as main factor in the models to account for variance incurred during learning. Results are presented by region.

6.2.4 Results of the Experiment V in children

There was a very strong effect ($p < .001$) of the logarithmic term of position of the item in the experiment in all regions indicating a large effect of learning.

Verb

Region 2: verb region.

There is no effect of Inflectional entropy on reading times at the verb region ($\beta = -.006, SE = .083, t = -.075, p = 0.94$). Data are plotted in Figure 6.1.

Object

Region 6: object region.

A main effect of Object type ($\beta = -.057, SE = .021, t = -2.696, p < .05$) was attested at the region of the object. As seen in the plotted data in Figure 6.2, reflexives are read overall faster than proper names, replicating the performance of the Greek-speaking adults.

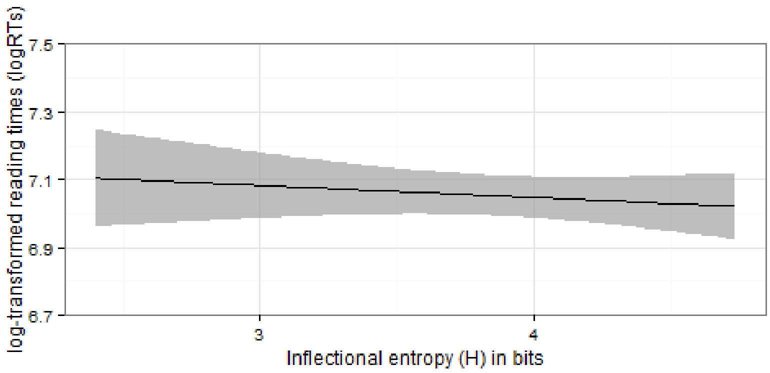


Figure 6.1: (Children) VERB REGION
Although there is a numerical trend, at the region of the verb of the facilitation of InflH on RTs at the verb region, it did not reach significance. Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the logRTs.

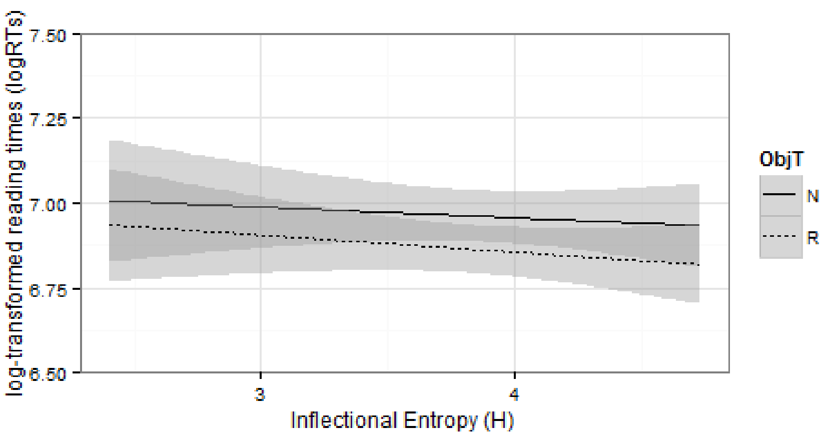


Figure 6.2: (Children) OBJECT REGION
Reflexives are read significantly faster than proper names and RTs are not influenced by the value of InflH. Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the logRTs for each Object type condition ('N'= proper name and 'R'=reflexive).

Pronoun

Region 12: pronoun region.

Inflectional entropy has a main effect on reading times ($\beta = -.079, SE = .035, t = -2.162, p < .05$). Processing of the pronoun is facilitated in the higher values of InflH (Figure 6.4).

Region 14: second spillover region after the pronoun.

A main effect of InflH ($\beta = -.096, SE = .04, t = -2.268, p < .05$), two spillover regions after the pronoun attests that reading times get significantly lower in the higher values of InflH, for both conditions. Data are plotted in Figure 6.4.

6.3 Summary of Experiment V

In all the experiments with adults presented so far, a facilitation effect of first activation of verbs with higher values of InflH has been attested. The data from the experiment with children failed however to reach significance at the point of the verb retrieval. For the other regions of interest, their performance patterns to a great degree with that of Greek adults. There is no interaction between the proper name and the reflexive at the object position but reflexives are read significantly faster. Children, already at the region of the pronoun, are facilitated by higher values InflH.

6.4 Discussion

This experiment was conducted in order to investigate the developmental aspect of the computational system. Before discussing the findings I must say that children at the age 7 and 8 years are almost too old. The reading task however does not allow testing children below the age of 6 or 7. In fact, the experiment was first conducted in younger children.

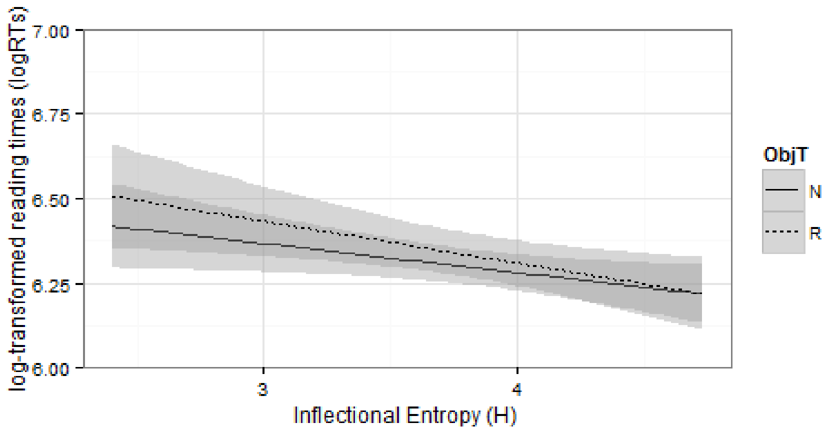


Figure 6.3: (Children) Pronoun region
Processing of the pronoun is facilitated in the higher values of InflH for both conditions. High InflH events are re-accessed faster than low InflH ones. Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the logRTs for each Object type condition ('N'= proper name and 'R'=reflexive).

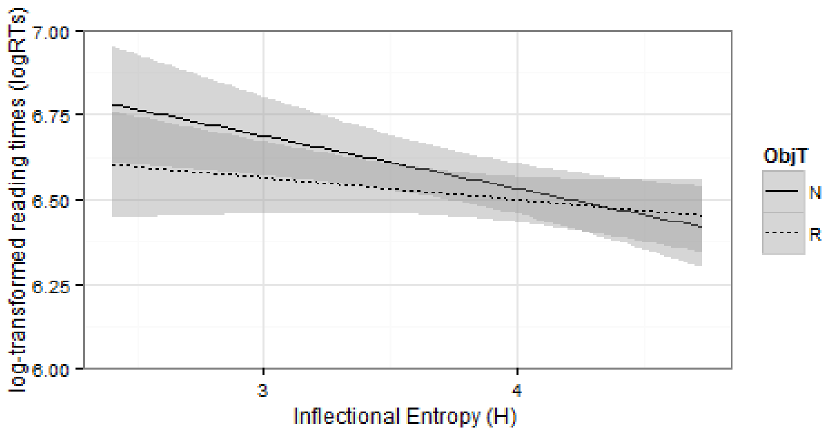


Figure 6.4: (children) Second spillover region after the pronoun
Reading times are significantly lower for higher values of InflH. Gray shaded areas indicate 95% confidence intervals around regression lines that relate InflH to the logRTs for each Object type condition ('N'= proper name and 'R'=reflexive).

These, however, got tired from reading already at the first 15 items they completed. Still, the data provide some information on children's online processing and are therefore included. More precisely, the data suggest that children at the age that they can read, are old enough and have enough processing resources, as their processing behaviour is very similar to that of Greek speaking adults. Nevertheless, children appear to not be facilitated by the value of InflH at the region of the verb, unlike the Greek adults for which the effect was very strong. One could claim that this supports H4, namely that their processing resources are limited. but that could not explain the fast processing of reflexives at the object region and the strong facilitation of InflH at the pronoun position. The data thus support H6, namely that the connections of the paradigm in LTM have not yet reached the adult-like state. As such the Activation Potential of the verbs is lower, suggesting that the lack of a main effect of InflH at the verb position reflects a "floor effect": verbs were processed equally fast (at least to be detected by that particular task). At the pronoun region both conditions are facilitated in the higher values of InflH for two independent reasons, as the third column of the model in Section 3.6 would predict. The Self-events are accessed really fast because the trace of their representation in WM is very strong: the verb of the event had a weak trace because of its high AP (although stronger for children than for adults) and was even strengthened by the processing effort consumed when the verb was re-addressed for the interpretation of the anaphoric expression. The NP-events with verbs of highInflH are the ones that used the (relatively) smallest amount of processing resources since the activation of their verb was (for children relatively) easy and the PN added to its complexity, so the high availability in resources of the processor accelerates their re-accessing.

To conclude, children at this age seem to have neither lower capacity nor lower processing speed. It seems rather that lexical items (the verbal paradigms at least) in their mental lexicon are not yet connected in such an established way as in adults resulting to an overall lower AP of the inflected verbs forms. In fact, it has been again reported that children with a processing capacity similar to that of adults, showed substantial difference in the contents of the LTM (Chi, 1976). Clearly, further research with more participants and a more sensitive task would give a clearer insight in the time course of the processor's development.

CHAPTER 7

Summary

It all started from the often made claim that sentence processing difficulties are the result of the "limited processing capacity of the processing system" and, as already mentioned, the term "capacity" can refer to either the available *space* or to the amount of *information* that a system can compute in a given time. Clearly the "capacity" can reach the stage of being "limited" when the system has to compute a task that has challenging demands either in terms of space or in terms of information. Sentence processing consists of, very roughly, receiving signals, identifying their corresponding entries in the mental lexicon and integrating them into the structure, and all these in minimum time and in a cognitive system that does have limitations.

The puzzle that gave rise to this project was how this interplay, between the linguistic requirements and the system's limitations, can "challenge" the system and influence the speed of sentence processing. In fact, instead of investigating structural complexity, or excessive cognitive task-related demands, I concentrated on (admittedly) simple sentences and on a population that is uniform enough to be assumed to have (roughly) the same capacity in terms of *space*, and looked into the way that a property of lexical items, and more precisely their organization in the mental lexicon, affected the speed of processing of the whole sentence. The results presented in this study indicate that processing difficulties exist even in simple structures and result from the trade-off between both linguistic and memory constraints. As a matter of fact, the findings attest that the way that lexical items are connected to their neighbours (inside their inflectional paradigm) influences their level of activation (in LTM), which in turn differentiates their level of representation (trace) in online computations (in WM). Depending on the amount of the resources that are still available in the system, the lexical items are integrated and re-accessed with a higher or lower speed.

I followed the cue-based interference model of sentence comprehension proposed by Lewis & Vasishth (2005), which describes, and computationally quantifies, the time course of sentence processing in WM. The model, based on the cognitive ACT-R architecture (Anderson and Lebiere, 1998; Anderson et al., 2004; Anderson, 2005b) posits that processing delays result from interference during retrieval, which is induced by the similarity between the target and the already processed items (and constituents). I zoomed in on the stage of *lexical activation* (a stage that L&V deliberately do not discuss in detail), assumed that interference effects should be present across the board and looked at the representational similarity of lexical items inside the networks they are connected in LTM, and more precisely inside their closest network, namely the inflectional paradigm.

I proposed that the *Activation Potential* of a lexical item, that is, a lexical item's *accessibility*, depends, among other factors, on the degree of the representational similarity of its inflectional paradigm, and crucially that the level of AP is related to the processing effort exerted for the item's activation and reflected in the prominence of the item's trace in WM. As a result, AP is, indirectly, connected to the speed with which subsequent elements of the sentence will be computed, and should thus be considered when examining processing complexity. To quantify the degree of similarity among the members of an inflectional paradigm I used an information theoretic measure, the Inflectional entropy of a verbal paradigm, which is a function of the ratio of each inflected item's frequency to the functions/meanings it can serve. The reason that InflH was chosen for this quantification was that the value of the InflH describes the uniformity of a paradigm's representation, with more uniform paradigms having higher values of InflH. Furthermore, InflH has been shown to correlate with processing speed both in production and in comprehension (Section 3.4). I claimed that the *Base level of activation*, used in the L&V framework to describe a part of lexical access, is, along with InflH (and other factors still to be investigated) one of the factors that determine the Activation Potential of each lexical item. If the task contains no "search-to-find" process, like the task of language comprehension, then a high degree of representational similarity (high InflH) increases the level of a lexical item's AP (Section 3.6).

As already mentioned, the experiments I conducted were designed in such a way as to keep structural complexity and cognitive demands as low as possible, which was achieved by using simple subject-verb-object sentences and a simple self-paced reading task. All the experiments were conducted in both a morphologically poor and a morphologically rich language (Dutch and Greek, respectively).

In the first set of experiments (Chapter 4), the structures used contained verbs of varying AP (as measured by their InflH) and were minimally modified in respect to the requirements of the object's interpretation: whether interpretation of the object required re-addressing of the verb (reflexive cases) or not (proper name cases). The questions asked were whether the first activation of a sentence's main verb influences the processing speed of its object, and how the processing resources are distributed during those computations. The particular modification with the reflexive was chosen for two reasons. First because resolving referential dependencies is a very fast process (see for instance Ruigendijk et al., 2006; Koornneef, 2008; Koornneef et al., 2011, for overviews), and as such reflexives could keep the processing demands (relatively) low, as wished. The particular implementation I used is based on Reuland and Winter (2009) and Reuland (2011), which follows an insight from the semantic literature (e.g. Keenan, 1988), that reflexives operate on the verb they are an argument of. Interestingly, the interpretation of the reflexive does not require an operation on the verb neither in the standard binding theory (Chomsky, 1981), nor in other approaches such as Safir (2004). Given this, my results also contribute to distinguishing between frameworks. From the experiments it was attested that the Activation Potential of a lexical item is proportional to the values of its paradigm's Inflectional entropy, as reading times were faster in verbs with higher values of Inflectional entropy. In addition, items that are activated fast due to their higher AP have a weak representation in WM, which makes them hard to re-address, as in the case of reflexives as objects of verbs with high InflH (discussed in Section 4.3). That the processing speed of the reflexive depends on the representational trace of the verb indicates that the interpretation of the reflexive does require an operation on the verb and provides independent evidence in favour of Reflexivity framework-based approaches. At the same time, when the system processes rich morphology, as in the case of Greek, it saves on resources and costly computations, such as re-addressing a weak trace for the interpretation of the reflexive, are accelerated (Section 4.4). The fact that the sentences between the two experiments differed in the lexical element used in the subject position (strong pronoun *hij*/ *zij* for Dutch versus proper name for Greek) did not allow analyses on the collapsed data. The between-language analyses did however show that interference effects appear already in the intra-sentential level when a proper name has already been activated (delay of Greek PN at the object position, discussed in Section 4.7).

In Chapter 5, the second set of experiments aimed to identify how processing speed evolves when the processing demands get higher. That was achieved by the insertion of a second clause, the interpretation of which required re-accessing the stored representation of the event created by the first clause. Analyses were conducted in each language separately, between-languages, and because the critical sentences were identical for the experiments in both languages, analyses on the collapsed data were allowed. The results for the first clause replicated the ones of the first set of experiments. The analysis of the collapsed data showed a clear advantage of processing speed (all other factors kept constant) for Greek in the first clause: Greek verbs were processed faster which, in turn, accelerated the integration of the proper name in the object position, in comparison to Dutch (Section 5.3). For the second clause it can be concluded that the trace of the representation of an event depends on how the event was processed: events that required a lot of processing effort have a stronger representational trace than those that are more economical. Furthermore, the ease of re-accessing a stored event is proportional to the cost of its processing: costlier events are accessed faster. The costly highInfl-Ref cases in Dutch and Greek were facilitated at the pronoun position as a result of the strong representation created during their processing. This was further attested by the analyses of the collapsed data where the difference in the direction of reading times between the object and the pronoun position is directly visible, suggesting that the "easy-to-activate-hard-to-re-access" principle applies also at the inter-sentential level. It was additionally observed that the system which saved on resources during processing of the first clause of a morphologically rich language like Greek, stored weaker representations of the events, and re-accessing them during the second clause required more effort. To the contrary in the system that processed poor morphology, like Dutch, slow processing during the first clause was compensated by strong representations of events that enabled their fast re-accessing during the second clause. This effect was present in all the analyses but it is shown more clearly in the between-language analyses where Dutch is slower at the object position but faster at the pronoun position than

Greek (Section 5.4).

Additionally, I attempted to lower the “threshold”of the system’s capacity and explore the extent to which the interaction between the level of AP and sentence processing has the same pattern, by looking into how children would process the sentences under study (Chapter 6). Unfortunately, the experimental task required that the children would be at an age that they can read (age of 7), which makes them almost too old to allow capturing any developmental changes (developmental changes have been attested to children usually up to the 5th or 6th year of age). Still, although children’s performance in the experiment resembles that of the adults, there are indications that it is not identical. Their mental lexicon might not have reached the adult-like state in terms of the strength of the connections among the members of the paradigm, resulting in lexical items with lower AP. This is a suggestion, and not so much a claim, due to the fact that the number of the participants was relatively small and that the task might not be the most suitable. If, however, this suggestion holds, then developmental research should consider lexical access more carefully.

As a reader’s digest:

- The Activation Potential of a lexical item in LTM describes the item’s accessibility.
- One of the factors that determine the amount of AP is the influence of the item’s inflectional paradigm.
- The network’s influence is quantified by the Inflectional entropy of its paradigm. When there is no “search-to-find” operation involved, AP correlates positively with the InflH.
- In comprehension there is no “search-to-find” operation involved so high Inflectional entropy increases the AP of the lexical item and facilitates its activation.

focusing on verbs

- The interpretation of a reflexive requires an operation *on* the verb. As such, processing speed of a reflexive depends (all other factors kept constant) on the strength of the trace of the verb's representation in WM.
- Processing a proper name as an object of a verb is a costly operation, especially at low values of InflH, where the resources are limited after the costly first activation of the verb.
- Interference effects arise even within a simple subject-verb-object sentence if the lexical expressions in the subject and object positions have identical feature characteristics.
- The strength of the trace of representation of events in WM proportionally to the effort consumed during their processing.
- Re-addressing (or re-accessing) a constituent stored in WM follows the "easy-to-activate-hard-to-re-access" principle both at the intra- and the inter-sentential level. A verb that was activated more slowly is re-addressed faster. In the same sense, re-accessing an event that was hard to process is faster.
- Computations that are, at first, costly, can be boosted by the fact that the processing system has a lot of resources. Similarly, computations that are, at first, economical, can be delayed due to an overloaded computational system.
- Children at a reading age (age of 7) have no underdeveloped computational system, in terms of resources. It seems however that in their mental lexicon the paradigms have not yet developed adult-like connections.

7.1 Take home message

This project dealt with the interaction between memory and language imposed constraints and showed that they go hand in hand in the course of sentence processing. The Inflectional entropy of a verbal paradigm, tightly connected to a language's morphological richness, proved to be a good way to quantify one of the factors that modulate an inflected verb type's accessibility (its *Activation Potential*) and quantify processing cost. Costly computations consume a lot of resources but therefore store stronger traces, preventing the processor from a subsequent overloading. Similarly, saving on resources may lead to excessive processing effort at the subsequent steps. This interplay holds at the inter- and intra-sentential, but also at the within- and between-language levels. In fact, although morphologically rich languages (like Greek) have longer words and more complicated paradigms, they actually benefit in terms of processing effort (at least at the first processing steps) compared to morphologically poor languages (like Dutch). Compensation for Dutch comes later on, when computations are accelerated because of the strong traces stored during effortful processing. To put it simply, suppose you have a (by now known) sentence like "Stavroula constantly supports *Sophia*, and I find it incredible", in its Dutch and in its Greek version. *Sophia* will be processed more slowly in Dutch than the Greek *Σοφία* but then, in turn, the 'Stavroula's support of *Sophia*'-Dutch event will be re-accessed and processed faster than the 'Stavroula's support of *Σοφία*'-Greek one. I take this to be a reflection of the necessary trade-off between *space* and *information* for the sake of successful real-time computations.

At least this will happen in the third person singular, with a verb in present tense, between Greek and Dutch. And this is how it all starts over again. In order to be able to generalize over the influence of lexical access in sentence processing, we should modulate one factor that participates in the interplay at a time, that is structural and cognitive complexity, then combine the factors, look into more languages, determine their position in the continuum and study the processing patterns in the same experimental material. As a matter of fact, I believe that line of processing time in the entropy continuum is not a straight one. Acquiring more data from different languages will enable a more precise allocation of the point after which easy computations become hard and before which hard computations are accelerated. So, some of the questions were answered, some others remain still unclear and, luckily, some new questions emerged.

Quantifying processing complexity remains complex, but we do know one bit more about how to do it. Actually, Richard Feynman said it already: *'You cannot say A is made of B. All mass is interaction'.*

APPENDIX A

A.1 Examples of calculating Inflectional entropy for Greek

Verb *epeno* (‘to praise’, in Greek): high*er* InflH

Lemma	Inflected verb type	Frequency=F	R	p=(F/R)/Sum(F/R)	IL= - $\log_2$p	H_i =-p*$\log_2$p	InflH = Sum (H_i)
επαινώ		SumF=8793					4.010
	επαίνεσε	60	1	0.175	2.515	0.440	
	επαινέσει	38	1	0.111	3.174	0.352	
	επαινεί	36	1	0.105	3.252	0.341	
	επαινέσω	27	1	0.079	3.667	0.289	
	επαινώ	20	1	0.058	4.100	0.239	
	επαινούν	19	1	0.055	4.174	0.231	
	επαινούσε	18	1	0.052	4.252	0.223	
	επαινέθηκε	16	1	0.047	4.422	0.206	
	επαινεθεί	15	1	0.044	4.515	0.197	
	επαινέσουμε	14	1	0.041	4.615	0.188	
	επαινούσαν	13	1	0.038	4.722	0.179	
	επαίνεσαν	12	1	0.035	4.837	0.169	
	επαινούμε	10	1	0.029	5.100	0.149	
	επαινώντας	10	1	0.029	5.100	0.149	
	επαινείται	9	1	0.026	5.252	0.138	
	επαινέσουν	6	1	0.017	5.837	0.102	
	επαίνεσα	5	1	0.015	6.100	0.089	
	επαινούνται	3	1	0.009	6.837	0.060	
	επαινέσαμε	3	1	0.009	6.837	0.060	
	επαινεθούν	2	1	0.006	7.422	0.043	
	επαινείτε	2	1	0.006	7.422	0.043	
	επαινέσετε	1	1	0.003	8.422	0.025	
	επαινέσατε	1	1	0.003	8.422	0.025	
	επαινείς	1	1	0.003	8.422	0.025	
	επαινεθείς	1	1	0.003	8.422	0.025	
	επαινέθηκαν	1	1	0.003	8.422	0.025	

Verb *efcharisto* ('to thank', in Greek): low*er* InflH

Lemma	Inflected verb type	Frequency=F	R	p=(F/R)/Sum(F/R)	IL= - $\log_2 p$	H_i =-p*$\log_2 p$	InflH = Sum (H_i)
ευχαριστώ		Sum=8793					2.403
	ευχαριστώ	5186	1	0.590	0.762	0.449	
	ευχαριστούμε	1059	1	0.120	3.054	0.368	
	ευχαριστημένος	600	1	0.068	3.873	0.264	
	ευχαριστήσω	423	1	0.048	4.378	0.211	
	ευχαριστημένοι	328	1	0.037	4.745	0.177	
	ευχαρίστησε	328	1	0.037	4.745	0.177	
	ευχαριστεί	140	1	0.016	5.973	0.095	
	ευχαριστημένη	129	1	0.015	6.091	0.089	
	ευχαριστήσει	114	1	0.013	6.269	0.081	
	ευχαριστήσουμε	68	1	0.008	7.015	0.054	
	ευχαριστώντας	36	1	0.004	7.932	0.032	
	ευχαριστούσε	33	1	0.004	8.058	0.030	
	ευχαριστήθηκε	33	1	0.004	8.058	0.030	
	ευχαρίστησαν	28	1	0.003	8.295	0.026	
	ευχαριστούν	25	1	0.003	8.458	0.024	
	ευχαριστήσουν	19	1	0.002	8.854	0.019	
	ευχαριστημένο	19	1	0.002	8.854	0.019	
	ευχαρίστησα	19	1	0.002	8.854	0.019	
	ευχαριστηθεί	16	1	0.002	9.102	0.017	
	ευχαριστημένους	13	1	0.001	9.402	0.014	
	ευχαριστημένα	13	1	0.001	9.402	0.014	
	ευχαριστήθηκα	12	1	0.001	9.517	0.013	
	ευχαριστημένες	12	1	0.001	9.517	0.013	
	ευχαριστιέται	11	1	0.001	9.643	0.012	
	ευχαριστήσαμε	10	1	0.001	9.780	0.011	
	ευχαριστούσαν	10	1	0.001	9.780	0.011	
	ευχαριστιούνται	10	1	0.001	9.780	0.011	
	ευχαριστιέμαι	9	1	0.001	9.932	0.010	
	ευχαριστιόταν	9	1	0.001	9.932	0.010	
	ευχαριστήθηκαν	9	1	0.001	9.932	0.010	
	ευχαριστήσεις	9	1	0.001	9.932	0.010	
	ευχαριστηθώ	7	1	0.001	10.295	0.008	
	ευχαριστηθούμε	7	1	0.001	10.295	0.008	
	ευχαριστηθήκαμε	6	1	0.001	10.517	0.007	
	ευχαριστήσετε	5	1	0.001	10.780	0.006	
	ευχαριστείς	4	1	0.000	11.102	0.005	
	ευχαριστηθείς	4	1	0.000	11.102	0.005	
	ευχαριστηθείτε	4	1	0.000	11.102	0.005	
	ευχαριστείτε	4	1	0.000	11.102	0.005	
	ευχαριστηθούν	4	1	0.000	11.102	0.005	
	ευχαριστιόμουν	3	1	0.000	11.517	0.004	
	ευχαριστιόμαστε	3	1	0.000	11.517	0.004	
	ευχαριστιέσαι	3	1	0.000	11.517	0.004	
	ευχαριστούσα	2	1	0.000	12.102	0.003	
	ευχαριστούσαμε	1	1	0.000	13.102	0.001	
	ευχαριστούνταν	1	1	0.000	13.102	0.001	
	ευχαριστημένης	1	1	0.000	13.102	0.001	
	ευχαριστηθήκατε	1	1	0.000	13.102	0.001	
	ευχαριστείται	1	1	0.000	13.102	0.001	
	ευχαριστήσατε	1	1	0.000	13.102	0.001	
	ευχαριστήστε	1	1	0.000	13.102	0.001	

A.2 Values of inflectional entropy of the experimental items

Table A.1: Dutch - Experiment I

	Verb	translation	InflH
1	SCHEIDT	separate	1.043
2	BINDT	binds	1.268
3	VLEIT	flatters	1.324
4	DWINGT	pushes	1.347
5	PRIJST	praises	1.476
6	DANKT	thanks	1.517
7	VOEDT	feeds	1.539
8	SLUIT	closes	1.583
9	TREEFT	meets	1.756
10	STRIJKT	caress	1.773
11	WERFT	throws	1.913
12	WEKT	wakes up	1.932
13	SNAPT	comes to understanding	2.068
14	LEIDT	leeds	2.068
15	WRIJFT	rubs	2.139
16	KNIJPT	pinches	2.150
17	HELPT	helps	2.183
18	TOONT	demonstrates	2.195
19	BRANDT	burns	2.198
20	ROEPT	calls	2.206
21	VRAAGT	asks	2.223
22	SLEURT	drags	2.266
23	SLAAT	hits	2.272
24	SLEEPT	drags	2.323

Table A.2: Greek Experiment II

	Verb	translation	InflH
1	EFCHARISTI	thanks	2.043
2	KRITIKARI	criticizes	2.656
3	PIEZI	flatters	3.045
4	EPIPLITI	admonishes	2.857
5	KATAKRINI	castigates	3.392
6	VOITHAI	helps	3.822
7	KATIGHORI	blames	3.968
8	AMFISVITI	questions	3.987
9	EPENI	praises	4.01
10	KOROIDEVI	mocks	4.154
11	THAFMAZI	admires	4.157
12	STIRIZI	supports	4.194
13	PROSTATEVI	protects	4.502
14	IPOTIMAI	belittles	4.638
15	ADIKI	wrongs	4.730
16	SIGCHERI	congratulates	3.158
17	KATHISICHAZI	calms	3.236
18	PITHI	persuades	4.270
19	EKSANTLI	exhausts	4.09
20	PROETIMAZI	prepeares	4.721
21	PROSEHI	is attentive	4.41
22	TROFODOTI	feeds	3.53
23	APORIPTI	disregards	3.972
24	KATALAVENI	understands	4.025

Table A.3: Dutch - Experiment III

	Verb	translation	InflH
1	SCHEIDT	separate	1.043
3	VLEIT	flatters	1.324
4	DWINGT	pushes	1.347
5	PRIJST	praises	1.476
6	DANKT	thanks	1.517
7	VOEDT	feeds	1.539
8	WEKT	wakes up	1.932
9	SNAPT	comes to understanding	2.068
10	LEIDT	leeds	2.068
11	WRIJFT	rubs	2.139
12	KNIJPT	pinches	2.150
13	HELPT	helps	2.183
14	TOONT	demonstrates	2.195
15	ROEPT	calls	2.206
16	SLAAT	hits	2.272

Table A.4: Greek - Experiment IV

	Verb	translation	InflH
1	EFCHARISTI	thanks	2.043
2	KRITIKARI	criticizes	2.656
3	PIEZI	flatters	3.045
4	EPIPLITI	admonishes	2.857
5	KATAKRINI	castigates	3.392
6	VOITHAI	helps	3.822
7	KATIGHORI	blames	3.968
8	AMFISVITI	questions	3.987
9	EPENI	praises	4.01
10	KOROIDEVI	mocks	4.154
11	THAFMAZI	admires	4.157
12	STIRIZI	supports	4.194
13	PROSTATEVI	protects	4.502
14	IPOTIMAI	belittle	4.638
15	ADIKI	wrongs	4.730
16	SIGCHERI	congratulates	3.158

Table A.5: Greek children - Experiment V

	Verb	translation	InflH
1	efcharisti	thanks	2.043
2	maloni	scolds	2.656
3	piezi	flatters	3.045
4	voithai	helps	3.822
5	katighori	blames	3.968
6	amfisviti	questions	3.987
7	epeni	praises	4.01
8	koroidevi	mocks	4.154
9	thafmazi	admires	4.157
10	prostatevi	protects	4.502
11	adiki	wrongs	4.730
12	sigcheri	congratulates	3.158

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Samenvatting in het Nederlands

1. Inleiding

Zinsverwerking bestaat ruwweg uit het ontvangen van signalen, het identificeren van de daarmee corresponderende eenheden (woorden of onderdelen daarvan) in het mentale lexicon en het integreren van deze eenheden in een structuur. Deze processen zijn gebaseerd op taalspecifieke kenmerken van de input, zowel lexicaal als structureel, en worden beïnvloed door het feit dat het cognitieve systeem een beperkte verwerkingscapaciteit heeft in termen van *ruimte* en/of de hoeveelheid *informatie* die het systeem kan verwerken op een bepaald moment. Lexicale kennis, taalstructuur en verwerkingscapaciteit (waaronder geheugen), zijn dus samen met onze kennis van de wereld, de hoofdingrediënten van het proces dat leidt tot taalbegrip. De snelheid waarmee we informatie van al die verschillende bronnen kunnen combineren en verwerken, gegeven dat we in staat zijn om deel te nemen aan conversaties op een normaal tempo, is verbazingwekkend en intrigerend. Dit project behandelt de interactie tussen door geheugen en door taal opgelegde eisen en onderzoekt de rol van de organisatie van de vervoegingen (uitgangen) van werkwoorden (het 'inflectioneel paradigma') op de snelheid van zinsverwerking.

2. Geheugen, informatietheorie en zinsverwerking

Ik baseer me op het taalverwerkingsmodel van zinsbegrip zoals voorgesteld door (Lewis and Vasishth, 2005; Lewis et al., 2006) dat het tijdspad van zinsverwerking in het werkgeheugen (WG) beschrijft en computationeel kwantificeert. Het model veronderstelt dat vertraging in de verwerking het gevolg is van interferentie tijdens het ophalen van elementen uit het geheugen. Die interferentie treedt op wanneer het doelelement en de al verwerkte elementen (en constituenten) teveel op elkaar lijken. Ik richt me met name op het stadium van lexicale activatie (een stadium dat L&V opzettelijk niet in detail bespreken). Mijn hypothese is dat interferentie-effecten aanwezig zouden moeten zijn over de hele linie en ik bekijk in verband hiermee de rol van gelijkenis van verwante lexicale elementen (elementen die horen tot hetzelfde 'inflectioneel paradigma') in het langetermijngeheugen (LTG).

De mate van gelijkenis tussen de leden van een inflectioneel paradigma kunnen we uitdrukken als een getal door middel van de *inflectionele entropie* (InflH) van het werkwoordparadigma (een maat uit de informatietheorie van Shannon, 1948), die we verkrijgen door de frequentie (F) van ieder vervoegd element te delen door het aantal functies/betekenissen (R) die het draagt (Formule 1). De waarde van InflH beschrijft de uniformiteit van de representatie van een paradigma, waarbij de waarde van InflH hoger is naarmate het paradigma meer uniform is. Er is aangetoond dat er een correlatie is tussen InflH en verwerkingssnelheid, zowel in productie (e.g. Baayen and Moscoso del Prado Martín, 2005; Tabak et al., 2005) als in begrip (e.g. Kostić and Havelka, 2002; Tabak et al., 2005, 2010; van Ewijk, 2013).

1. Inflectionele entropie van een inflectioneel paradigma:

$$H_p = -\sum_{i=1}^{c} \frac{\frac{F_i}{R_i}}{\sum_{j=1}^{c} \frac{F_j}{R_j}} \times \log_2 \frac{\frac{F_i}{R_i}}{\sum_{j=1}^{c} \frac{F_j}{R_j}},$$

Ik stel voor dat de *toegankelijkheid* van een lexicaal element, wat ik het *Activatiepotentieel* (AP) noem, onder andere afhangt van de InflH van een paradigma (2).

2. Informatietheoretische kwantificatie van het Activatiepotentieel van een werkwoord i in het LTG:

$$AP_i = \mathit{InflH} = -\sum_{i=1}^{c} \frac{\frac{F_i}{R_i}}{\sum_{j=1}^{c} \frac{F_j}{R_j}} \times \log_2 \frac{\frac{F_i}{R_i}}{\sum_{j=1}^{c} \frac{F_j}{R_j}}$$

Cruciaal hierbij is dat het niveau van AP gerelateerd is aan de verwerkingsinspanning die wordt aangewend om een element te activeren en gereflecteerd is in de prominentie van de representatie van het element in het WG (zie 3 hieronder).

3. Kracht van de representatie van een geactiveerd element in het WG = $\frac{k}{AP_i} = \frac{k}{\mathit{InflH}}$, waarbij k de hoeveelheid vereiste energie is om 1 bit aan informatie te verwerken.

Een element met een laag AP heeft een sterke representatie in het WG als gevolg van het verbruiken van veel verwerkingsenergie. Tegelijkertijd heeft het systeem minder middelen over dan wanneer er een element met een hoger AP wordt geactiveerd. Dat wil zeggen, zwakke sporen (van elementen met een hoge AP) bestaan in een systeem met een hoop beschikbare verwerkingsruimte. Sterke sporen (van elementen met een laage AP) bestaan in een systeem met minder beschikbare verwerkingsruimte.

De experimenten zijn zodanig opgezet dat structurele complexiteit en cognitieve vereisten tot een minimum worden beperkt door eenvoudige subject-werkwoord-object zinnen te gebruiken en een eenvoudige self-paced-reading taak te gebruiken. Alle experimenten zijn uitgevoerd in zowel een morfologisch arme als een morfologisch rijke taal (respectievelijk het Nederlands en het Grieks), omdat de eerste over werkwoorden beschikt met lagere waarden voor InflH dan de laatste, zodat er dus meer verwerkingsmiddelen worden verbruikt tijdens de eerste activatie. De voorspellingen van het model voor elementen met verschillende waarden voor InflH zijn opgesomd in Tabel A hieronder.

Tabel A: De snelheid van toegang hangt af van het AP van een lexicaal element. De sterkte van het spoor is proportioneel aan de snelheid van toegang. Heractivatie vergroot de sterkte. De snelheid van heractiveren wordt gemoduleerd door het spoor van het ´terug-te-halen lexicale element'. Als er geen heractivatie aan te pas komt hangt de snelheid van verwerking bij de tweede stap af van de hoeveelheid beschikbare verwerkingsruimte die er over is in het systeem. Langzame berekeningen vereisen een hoop inspanning (en verwerkingsmiddelen).

		Verwerkingsstap 1 (uit LTM)	Verwerkingsstap 2 (in WG)	
		Eerste activatie	heractivatie	Geen heractivatie
Lage AP	snelheid van toegang	langzaam	snel	n.v.t.
	sterkte van het spoor	sterk	sterk(er)	sterk
	verbruikte verwerkingsmiddelen	+++	+	procesafhankelijk
	snelheid van verwerken tijdens de verwerkingsstap	snel	langzaam	
Hoge AP	snelheid van toegang	snel	langzaam	n.v.t.
	sterkte van het spoor	zwak	sterk	zwak(ker)
	verbruikte verwerkingsmiddelen	+	+++	procesafhankelijk
	snelheid van verwerken tijdens de verwerkingsstap	snel	langzaam	snel

Noot: Het aantal "+" representeert de hoeveelheid verbruikte verwerkingsmiddelen bij iedere stap.

3. Inflectie, toegankelijkheid, en heractivatie in de zinsverwerking

In de eerste serie experimenten bevatten de gebruikte structuren werkwoorden met uiteenlopende APs (gemeten aan hun InflH) en ze vertoonden verder een minimale variatie, namelijk alleen in de aard van de relatie met het object. Voor één groep zinnen vereiste interpretatie van het object heractivatie van het werkwoord (in het geval van een reflexief), voor een andere groep niet (in het geval van een eigennaam). Een voorbeeld van de testzinnen is te zien in (4).

4. Peter prijst Helen/zichzelf en niet zijn andere collega's

De vragen die zijn gesteld waren of de eerste activatie van het hoofdwerkwoord van een zin van invloed is op de verwerkingssnelheid van het bijbehorende object en hoe de verwerkingsmiddelen zijn verdeeld gedurende deze berekeningen. Een reflexief is gekozen om twee redenen. Ten eerste, omdat het oplossen van referentiële afhankelijkheden een zeer snel proces is (zie bijvoorbeeld Ruigendijk et al., 2006; Koornneef, 2008; Koornneef et al., 2011, voor een overzicht), en reflexieven de verwerkingsvereisten (relatief) laag kunnen houden zoals gewenst. De specifieke implementatie die ik heb gebruikt is gebaseerd op Reuland en Winter (2009) en Reuland (2011) waar een inzicht vanuit de semantische literatuur wordt gevolgd (e.g. Keenan, 1988), namelijk dat reflexieven opereren op het werkwoord waarvan ze een argument zijn. Interessant is dat de interpretatie van het reflexief geen operatie op het werkwoord vereist in de standaard bindingstheorie (Chomsky, 1981), noch in andere benaderingen zoals Safir (2004). Daarom dragen de resultaten van de experimenten ook bij aan het onderscheiden van de verschillende benaderingen. De experimenten laten zien dat elementen die snel geactiveerd worden, als gevolg van een hoger AP, een zwakke representatie hebben in het WG, wat het moeilijk maakt om ze te heractiveren, zoals in het geval van reflexieven als object van een werkwoord met een hoge InflH. Dat de verwerkingssnelheid van het reflexief afhangt van de representatie van het werkwoord duidt erop dat de interpretatie van een reflexief wel degelijk een operatie op het werkwoord vereist en biedt zo onafhankelijk bewijs ten gunste van benaderingen die op het Reflexivity-kader zijn gebaseerd. Tegelijkertijd wordt er, als het systeem rijke morfologie verwerkt, zoals in het geval van het Grieks, bespaard op verwerkingsmiddelen en kostbare berekeningen. Het heroproepen van een zwakke representatie voor de interpretatie van een reflexief als object van een werkwoord met een hoog InflH gaat bijvoorbeeld sneller.

De tweede serie experimenten had als doel om vast te stellen hoe de verwerkingssnelheid zich ontwikkelt wanneer de verwerkingsvraag groter wordt. Dat is bereikt door een tweede zinsdeel in te voegen waarvan de interpretatie het heroproepen van een opgeslagen representatie van een gebeurtenis vereiste die werd gevormd door het eerste zinsdeel (voorbeeld in (5)).

5. Helen prijst Peter/zichzelf *en ik vind* ***dat*** *schattig*

De data zijn geanalyseerd voor iedere taal afzonderlijk, tussen talen, en voor de samengevoegde data. De resultaten met betrekking tot het eerste zinsdeel repliceren de resultaten van de eerste serie experimenten. De analyse van de samengevoegde data laat een duidelijk voordeel in verwerkingssnelheid zien voor het Grieks in het eerste zinsdeel (alle andere factoren werden gelijk gehouden): Griekse werkwoorden werden significant sneller verwerkt, wat op zichzelf weer de integratie van de eigennaam in objectpositie versnelde in vergelijking tot het Nederlands. In de tweede zin verwijst het voornaamwoord naar de gebeurtenis die aangeduid wordt door de eerste zin. Voor het tweede zinsdeel kan worden geconcludeerd dat de representatie van een gebeurtenis afhankelijk is van hoe de gebeurtenis werd verwerkt: gebeurtenissen die een grote hoeveelheid verwerkingsinspanning vereisen, hebben een sterker representationeel spoor dan degene die minder kostbaar zijn. Verder is het gemak van het heroproepen van een gebeurtenissen proportioneel aan de kosten van het verwerken ervan: kostbaardere gebeurtenissen worden sneller bereikt, wat suggereert dat het "makkelijk-te-activeren-moeilijk-om-terug-te-halen" principe ook van toepassing is op een inter-sententieel niveau. Er werd daarnaast geobserveerd dat het systeem dat bespaarde op verwerkingsmiddelen tijdens het verwerken van het eerste zinsdeel van een morfologisch rijke taal zoals het Grieks, zwakkere representaties van gebeurtenissen opsloeg en dat het heroperoepen van de gebeurtenissen tijdens het tweede zinsdeel meer inspanning vereiste. In tegenstelling hiertoe werd in het systeem met een arme morfologie (het Nederlands) een langzame verwerking gedurende het eerste zinsdeel gecompenseerd door sterkere representaties van gebeurtenissen wat op zichzelf het sneller terughalen ervan in het tweede zinsdeel mogelijk maakts: het Nederlands is langzamer op de objectpositie, maar sneller op de positie van het pronomen dan het Grieks.

Daarnaast heb ik geprobeerd om de drempelwaarde van de capaciteit van het systeem te verlagen en uit te zoeken tot op welke hoogte de interactie tussen het AP-niveau en de zinsverwerking hetzelfde patroon heeft door te kijken naar hoe kinderen de zinnen in kwestie verwerken. Helaas vereiste de experimentele taak dat de kinderen van een leeftijd waren waarop ze konden lezen (zeven jaar), wat de kinderen bijna te oud maakt om veranderingen in de ontwikkeling in kaart te brengen (veranderingen in de ontwikkeling zijn aangetoond bij kinderen tot een leeftijd van vijf of zes jaar). Echter, ondanks dat het gedrag van de kinderen in het experiment gelijkenis vertoont met dat van de volwassenen, zijn er aanwijzingen dat het niet identiek is. Hun mentale lexicon heeft wellicht nog niet de volwassen staat bereikt in termen van de kracht van de verbindingen tussen de leden van het paradigma, wat leidt tot lexicale elementen met een lagere AP. Dit is meer een suggestie dan een claim, omdat het aantal deelnemers relatief klein was en de taak wellicht niet de meest geschikte was. Echter, als deze suggestie overeind blijft, dan zou taalontwikkelingsonderzoek nauwkeuriger moeten kijken naar lexicale toegankelijkheid.

Take home message

In een notedop, in een zin als “Stavroula ondersteunt *Sophia* altijd, en ik vind dat ongelofelijk”, in de Nederlandse en Griekse versie, *Sophia* langzamer verwerkt worden dan het Griekse $\Sigma o\phi\acute{\iota}\alpha$. Maar daar staat tegenover dat het Nederlandse 'Stavroula ondersteunt *Sophia*'-gebeurtenis sneller zal worden opgeroepen en verwerkt dan het Griekse 'Stavroula ondersteunt $\Sigma o\phi\acute{\iota}\alpha$'-gebeurtenis. Ik veronderstel dat dit een afspiegeling is van de noodzakelijke trade-off tussen *verwerkingsruimte* en *informatie* omwille van succesvolle *realtime* interpretatieprocedures (opgevat als een soort berekeningen van een interpretatie).

Op zijn minst zal dit gebeuren in de derde persoon enkelvoud met een werkwoord in de tegenwoordige tijd als we het Grieks en het Nederlands met elkaar vergelijken. En hier begint het weer opnieuw. Om te kunnen generaliseren over de invloed van lexicale toegankelijkheid in de zinsverwerking, zullen we per keer steeds één factor die deel uitmaakt van het samenspel moeten variëren. Dat wil zeggen, structurele en cognitieve complexiteit, dan deze factoren combineren, meer talen bekijken, hun positie op het continuüm bepalen en de verwerkingspatronen in hetzelfde experimentele materiaal bestuderen.

In feite geloof ik dat de relatie tussen verwerkingstijd en het continuüm van de entropie geen rechtstreekse relatie is. Het verzamelen van meer data in verschillende talen zal ons in staat stellen om het punt aan te wijzen waarna makkelijke berekeningen moeilijk worden en waarvóór moeilijke berekeningen versneld worden. Er zijn dus enkele vragen beantwoord, maar andere vragen blijven onduidelijk en gelukkig zijn er ook enkele nieuwe vragen ontstaan.

Verwerkinscomplexiteit kwantificeren blijft een complexe aangelegenheid, maar we weten één bit meer over hoe we dat moeten aanpakken. Eigenlijk zei Richard Feynman het al: "*Je kunt niet zeggen dat A is gemaakt van B. Alle massa is interactie*".

*** Als een "reader's digest" ***

- Het Activatiepotentieel van een lexical element in het LTG beschrijft de toegankelijkheid van een element.
- Eén van de factoren die de hoeveelheid AP bepalen is de invloed van het inflectioneel paradigma van het element.
- De invloed van het netwerk wordt gekwantificeerd door de inflectionele entropie van het paradigma. Als er geen "zoek-om-te-vinden"-operatie bij betrokken is dan is er een positieve correlatie tussen het AP en de InflH.
- In zinsbegrip is er geen "zoek-om-te-vinden"-operatie bij betrokken en dus vergroot een hoge inflectionele entropie het AP van een lexicaal element en vergemakkelijkt het daarmee de activatie.

als we ons focussen op werkwoorden

- De interpretatie van een reflexief vereist een operatie *op* het werkwoord. Daarom is de verwerkingssnelheid van een reflexief (als we alle andere factoren gelijk houden) afhankelijk van de kracht van de representatie van het werkwoord in het WG.
- Het verwerken van een eigennaam als object van een werkwoord is een kostbare operatie. Met name wanneer de InflH laag is, waarbij de verwerkingsmiddelen beperkt zijn na de kostbare eerste activatie van het werkwoord.
- Interferentie-effecten ontstaan zelfs binnen eenvoudige zinnen van het type subject-werkwoord-object als de elementen in subject- en object-positie teveel kenmerken delen.
- De kracht van de representatie van gebeurtenissen in het WG is proportioneel aan de verbruikte inspanning gedurende de verwerking ervan.
- Het heractiveren (of terughalen) van een constituent dat opgeslagen is in het WG voldoet aan het "makkelijk-te-activeren-moeilijk-om-terug-te-halen"-principe, zowel op intra- als intersententieel niveau. Een werkwoord dat langzamer geactiveerd is, is sneller terug te halen. Op

dezelfde manier is het heroproepen van een gebeurtenis dat moeilijk te verwerken was, sneller.

- Berekeningen die in het begin kostbaar zijn, kunnen gestimuleerd worden door het feit dat het verwerkingssysteem een hoop beschikbare verwerkingsruimte heeft. Op dezelfde manier kunnen berekeningen die in beginsel goedkoop zijn, vertraagd worden door een overbelast computationeel systeem.
- Kinderen van een leeftijd waarop ze kunnen lezen (zeven jaar) hebben geen onderontwikkeld computationeel systeem als het gaat om verwerkingsmiddelen. Het lijkt er echter op dat in hun mentale lexicon de paradigma's nog geen volwassen connecties hebben ontwikkeld.

Curriculum Vitae

Sophia Manika was born on the 24^{th} of September 1981 in Athens, Greece. She studied Applied Mathematics and Physical sciences in the National Technical University of Athens (NTUA) from where she obtained an MSc with a thesis in Graph Theory and the "The Proofs of the 4-colour Theorem" in July 2005. In September of the same year, she moved to Utrecht, the Netherlands, to attend the MPhil research program in linguistics of UiL OTS. She spent the second year of the program in Massachusetts Institute of Technology, United States, where she worked on language disorders and wrote her thesis. She obtained her Master's degree (cum laude) from Utrecht University in August 2007 with a thesis on the clitic omission in Greek-speaking children with Specific Language Impairment. For the following 3 years she moved to Germany where she worked in various fields, and in September 2010 she returned to research and linguistics. Her individual PhD proposal was granted a 3-year financial support grant by the Utrecht Institute of Linguistics OTS, which, along with a 6-month extension grant of the "Stichting Taal-technologie" resulted in this thesis.