

## Chapter 7

# Sentence Parsing

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### 7.1 Introduction

The printed words you are reading now are the perceptible cornerstones of an otherwise invisible grammatical edifice that is automatically reconstructed in your mind. According to many psycholinguists, comprehending spoken, written or signed sentences involves building grammatical structures. This cognitive activity, usually called syntactic analysis or sentence parsing, includes assigning a word class (part-of-speech) to individual words, combining them into word groups or 'phrases', and establishing syntactic relationships between word groups. All these parsing decisions should harmonize not only with rules of grammar but also with the message intended by speaker, writer or signer. Although usually proceeding effortlessly and automatically, the parsing process may slow down, err, or even break down completely when the sentence is very long or contains difficult grammatical constructions. Characterizing the exact nature of such problems and explaining them in terms of underlying cognitive mechanisms are important objectives of the subfield of psycholinguistics called Human Sentence Processing (HSP).

Developing a working model of sentence parsing is impossible without adopting a grammatical formalism and the structure building operations specified in it. Nevertheless, a survey of the psycholinguistic parsing literature need not spell out these operations *in extenso* because the behaviorally important processing issues can be stated without a great deal of linguistic jargon.

Section 7.2 outlines the cognitive architecture responsible for sentence comprehension; various modules are distinguished, and the control structure of the sentence parser is characterized. Section 7.3 presents an overview of the key factors that have been shown to affect the parser's functioning and provide clues to its inner workings. Section 7.4 addresses two cross-linguistic issues that have stimulated a great deal of empirical work. Finally, Section 7.5 offers some conclusions and directions for future research.

For details concerning experimental methodology, which are beyond the scope of this chapter, I refer to the psycholinguistic handbook edited by Gernsbacher (1994). Friederici's chapter in this volume deals with electrophysiological and brain-imaging methods in particular.

## 7.2 Sentence Parsing and Sentence Comprehension

The sentence comprehension task is usually dissected into subtasks that correspond to linguistic levels of description:

- auditory and visual word recognition (phonological/orthographic level; see chapters by Zwitserlood, by Frauenfelder & Floccia, by Cutler, by Zwitserlood, all this volume)
- lexical and morphological processes (morphological level; see chapters by Schriefers, by Engelkamp & Rummer and by Ferstl & Flores d'Arcais, all in this volume)
- parsing (syntactic level; see chapter by Ferstl & Flores d'Arcais in this volume, and the present chapter)
- conceptual interpretation (semantic level; see chapter by Engelkamp & Rummer, in this volume for conceptual processes at the lexical level)
- referential processes (discourse or pragmatic level; see chapter by Vonk & Noordman, this volume).

As evidenced by an increasing body of empirical data, the cognitive modules that take care of these subtasks operate in parallel rather than sequentially, and exchange information in bottom-up and top-down directions. These interactions usually promote efficiency and accuracy but may be detrimental at times, namely, when different modules happen to compute and distribute conflicting pieces of information. The latter is exemplified by sentences that lead the reader or listener up the garden-path, such as the classic example *The horse raced past barn fell*. One of the factors contributing to the 'garden-path' character of this sentence is lexical in nature, namely, the rare usage of *raced* as past-participle in passive voice, causing a bias in favor of *raced* interpreted—incorrectly—as a past-tense main verb. A conceptual factor conspiring against the past-participle reading of *raced* is the information that horses make particularly good 'agents' of racing events. The garden-path character of this sentence can probably be alleviated by embedding it in a discourse that introduces two or more horses, only one of which being chased past a shed. Such a context promotes the interpretation of *raced past the barn* as a modifier serving to single out one of the story characters—a referential factor. Numerous experimental studies can be cited in support of the sensitivity of the sentence parser to lexical, conceptual, and referential factors. This example illustrates a key feature of the control structure of the human sentence parser: *interactivity*. Interactive parsers are the counterparts of 'autonomous' parsers, which at first rely on syntactic and word-class information alone, and only subsequently allow their initial decisions to be modified in view of detailed lexical, conceptual and referential information. The psychological reality of an autonomous syntactic parsing stage is extensively debated in the literature (e.g.,

see Frazier & Clifton, 1996; Tanenhaus & Trueswell, 1995; see also Mitchell, 1994; Garrod & Sanford, 1994; and Section 7.3.1 below).

The second central feature of the control structure of human parsing is *incrementality*. Parsing a sentence does not wait for an end-of-sentence signal but starts immediately upon recognition of the first input word. From there, the parser ‘consumes’ every new input word without unnecessary delay, exploiting extrasyntactic information as much as possible (Marslen-Wilson, 1975). The syntactic structure computed for a sentence therefore grows basically from left to right in a word-by-word fashion—in contrast with clause-by-clause parsing schedules that many psycholinguists adhered to in the sixties, in the early days of modern psycholinguistics (see the surveys by Fodor, Bever & Garrett, 1974, and Levelt, 1978).

The third feature is *bounded parallelism*. Natural languages tend to have a large number of vocabulary items whose word-class membership is indeterminate. Moreover, their grammars often allow a given string of words to be combined into several different syntactic configurations. (A wide-spread type of ‘syntactic ambiguities’ is called ‘attachment ambiguity’: the classic example is *The man saw the woman with the binoculars*, where the prepositional phrase can be attached as a modifier to *saw* or *woman*.) In sentential contexts, many ambiguities are ultimately resolved thanks to the filtering effect of grammatical constraints. In actual practice, though, a considerable proportion of sentences is left with multiple word-class or syntactic ambiguities. How does the sentence parser deal with this problem? Three theoretical alleys have been explored in the literature: (1) serial parsing, (2) parallel parsing, and (3) minimal-commitment parsing. (For a detailed discussion of the theoretical and empirical merits of these parsing models, see Mitchell, 1994; computational versions are reviewed by Kempen, 1996.)

A *serial* parser commits itself to one of the available options as soon as a choice point presents itself: if, further down the sentence, a problem is encountered, the parser backtracks to an earlier choice point, selects another option from the available set, and proceeds from there. This strategy economizes working memory capacity because at no point in time is there a need to store more than one syntactic structure. However, this advantage entails the risk of delays due to frequent backtracking and structure revision operations (‘reanalysis’). A *parallel* parser refuses to make a selection from among the alternative options offered at a choice point and computes several different syntactic configurations, one for each of the options. This parallel strategy taxes working memory capacity but obviates time consuming structure revisions. A *minimal-commitment* parser attempts to combine the best of both worlds. It computes only a single syntactic configuration at any choice point; however, like non-deterministic parsers, it avoids backtracking and reanalysis. To this purpose it resorts to a wait-and-see strategy: any decision or computation that runs the risk of having to be undone, is postponed in anticipation of disambiguating information downstream. Upon arrival of such information it catches up on any outstanding work.

The well-attested phenomena of garden-path sentences and revisions reveal the human parser's liability to premature decisions and rule out minimal commitment as a viable model of human sentence parsing<sup>1</sup>. This also applies to extreme versions of parallel parsing models, which compute and store *all* syntactic configurations compatible with the current input string and therefore never need to retract any decisions. However, a weak version of parallelism cannot be ruled out—a parser that, at some or all choice points, explores more than one alternative reading and carries these for at least a brief period of time. This strategy entails a certain risk of backtracking—although smaller than in case of a strictly serial model—but reduces the probability of overtaxing the parser's working memory (in comparison with a fully parallel model). MacDonald, Just & Carpenter (1992) provide experimental evidence in support of a limited form of parallelism in parsing. For the time being I conclude that *bounded parallelism* is best viewed as the human parser's response to word-class and syntactic ambiguity<sup>2</sup>.

Characterized in folkpsychological parlance, the sentence parser is an eager beaver ('incrementality'), sensitive to multifarious impressions ('interactivity') but also somewhat impetuous ('bounded parallelism', reanalysis)—indeed, it's only human!

### 7.3 Phenomena and Explanations

In this Section I present an overview of three groups of empirical phenomena that have been studied extensively. The explanations substantiate the control structure of the sentence parser as outlined in the previous Section and add further details.

#### 7.3.1 Syntactic Complexity and Processing Overload

One of the earliest parsing phenomena to draw systematic psycholinguistic attention was the remarkable difference in processing complexity between center-embedded clauses and their right-branching counterparts (e.g., Miller & Isard, 1964). Single embeddings of both types present no particular problems—compare (1a) and (1b)—, nor do doubly-embedded right-branching clauses (2a). But doubly center-embedded clauses tend to become incomprehensible (2b), unless conceptual factors help to sort out which roles are assigned to which referents (3).

(1a) *The intern who was supervised by the nurse had bothered the administrator,*

(1b) *The nurse supervised the intern who had bothered the administrator.*

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<sup>2</sup> These phenomena are not incompatible with the presence of deterministic components *within* the parser—components that never retract their initial decisions, not even in case of garden-path sentences that force drastic reanalysis. Marcus (1980) and Gorrell (1995) have proposed minimal-commitment models for parsing sentences that do not give rise to conscious garden-path effects. A probabilistic model of bounded-parallel parsing was recently proposed by Jurafsky, 1996.

- (2a) *The intern who the nurse supervised had bothered the administrator who lost the medical reports.* (Gibson, 1997)
- (2b) *The administrator who the intern who the nurse supervised had bothered lost the medical reports.*
- (3) *The vase that the maid that the agency hired dropped on the floor broke into a hundred pieces.* (Stolz, 1967)

A third type of embedded clauses, so-called cross-serial dependencies, has been studied by Bach, Brown & Marslen-Wilson (1986). An example from Dutch is given in (4a). The German translation equivalent (4b) contains a doubly center-embedded structure, whereas the English counterpart is right-branching. Bach et al. (1986) presented sentences like (4a) and (4b) to native speakers of Dutch and German, respectively, and obtained various measures of comprehensibility. The cross-serial structures turned out to be easier than the center-embeddings.

- (4a) *Jeanine heeft de mannen Hans de paarden helpen leren voeren.*  
*Joanna has the men Hans the horses help teach feed*
- (4b) *Johanna hat die Männer Hans die Pferde füttern lehren helfen.*  
*feed teach help*
- (4c) *Joanna (has) helped the men teach Hans to feed the horses.*

Very recently, Gibson (1997) has proposed a complexity metric that is in remarkably good agreement with processing loads as measured for a wide range of sentence structures. The metric follows from his Syntactic Prediction Locality Theory (SPLT), which assumes a limited pool of computational resources that is shared by two kinds of processes<sup>3</sup>:

- integrating new input into the syntactic and referential (discourse) structures that have already been built for earlier parts of the current input string, and
- storing syntactic predictions, that is, syntactic categories that are needed to complete the current input string as a grammatical sentence.

The ‘cost’ associated with both types of computations increase monotonically over time. More precisely, the cost is incremented each time a new discourse referent is introduced. Only NPs (objects) and verbs of VPs (events) count as referents. Therefore, when many discourse referents intervene between a new to-be-integrated input word (the source) and an older element (the target), the cost is high. Similarly, the memory cost of retaining the syntactic category of a prediction depends on the number of novel discourse referents intervening between the input word that originally gave rise to the prediction, and the current input word.

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<sup>3</sup> Just & Carpenter (1992) were the first to propose a parser model (CC-READER) where processing and storage activities draw from the same, limited source of working memory capacity.

- (5a) *The reporter who the senator attacked admitted the error.*  
 (5b) *The reporter who attacked the senator admitted the error.*  
 (5c) *De reporter die de senator aanviel gaf de fout toe.*

Consider the examples in (5a) and (5b), containing an object and subject relative clause, respectively. The integration cost profiles of for these sentences are similar, except at the position of the embedded verbs (*attacked*). Simplifying somewhat, integration of this verb in case of (5a) implies attaching to it a subject (*the senator*) and an object (*who*). In (5b), only the subject (*who*) needs to be attached; moreover, the latter action is less costly than establishing the link between *who* and *attacked* in (5a), where a new referent (*the senator*) intervenes. Likewise, (5a) taxes the storage capacity more heavily than (5b) does: the important difference is the prediction, launched by the relative pronoun *who*, of an embedded verb. This prediction has to be carried over intervening discourse referent *the senator* in case of (5a), but not (5b). Various experiments have indeed shown that object relatives are somewhat harder to understand than subject relatives.

Surprisingly, this empirical finding applies not only to English but to German and Dutch, although in both latter languages object and subject relatives have the same word order (for a detailed survey, see Kaan, 1997). Sentence (5c), for instance, the translation equivalent of both (5a) and (5b), is preferably interpreted as (5b). Gibson accounts for this bias by making the additional assumption that, at a point of ambiguity, the parser opts for storage economy and selects the simplest set of predictions. In case, of (5c), the interpretation of relative pronoun *die* (*who*) as the object, entails the prediction of both an embedded verb and a subject, whereas the subject reading of *die* only implies the prediction of a verb<sup>4</sup>.

The SPLT model predicts substantial processing load differences between doubly center-embedded and right-branching clauses (2a/b). Gibson's 1997 paper gives detailed computations for these cases, for the contrast between (4a) and (4b), and for quite a few other constructions.

- (6a) *The Republicans who the senator who I voted for chastised were trying to cut all benefits for veterans.*  
 (6b) *The Republicans who the senator who Ann/she/the citizens voted for chastised were trying to cut all benefits for veterans.*

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<sup>4</sup> However, alternative explanations of the preference for subject interpretation of ambiguous relative clauses cannot be ruled out as yet. The effect could originate, not from complexity *per se*, but from a 'configurational bias' to take the first NP of a clause to be the grammatical subject (see the list of processing strategies in Section 7.3.2 below), and/or from a conceptual bias to interpret the (animate) referent of the first NP as the thematic agent.

Before leaving SPLT, I should point out Gibson's empirical motive for measuring distance in terms of *new discourse referents* denoted by NPs and VPs rather than the NPs and VPs themselves. It has been observed in various studies that double center-embeddings (in a null context) tend to become somewhat easier when the most deeply embedded subject is replaced by an indexical pronoun (e.g., *you* or *I*). Gibson verified this in an as yet unpublished experiment with sentences such as (6a), which were rated as easier understandable than their counterparts (6b) with either a short name (*Ann*), a third-person pronoun (*she*) or a full NP (*the citizens*) substituting for *I*. The argument is that referents of indexical pronouns—namely, the speaker and the hearer—are always included in the discourse model and can be mentioned without processing cost.

### 7.3.2 Parsing Preferences and Garden-Path Sentences

The mechanisms underlying the interpretation of structural ambiguities have occupied a prominent position on the psycholinguistic research agenda ever since Bever's seminal 1970 paper. The stage for both theory formation and experimentation was set in influential papers by Kimball (1973) and Frazier & Fodor (1978). They proposed a set of perceptual strategies ('parsing principles') responsible for guiding the human sentence parser towards its initial choices, in particular, towards determining how to integrate new input into the current syntactic configuration. These syntax-oriented perceptual strategies together with further proposals about a limited-capacity processing architecture, were assumed to constitute the first stage of sentence comprehension. Extrasyntactic (conceptual, discourse, context) information could exert its influence only in a second stage, possibly leading to reanalysis of the input and revision of earlier choices. Over the past ten years, this two-stage model has been seriously challenged by experimental data, collected by means of increasingly refined and sensitive techniques, indicating that the parser is affected by extrasyntactic information immediately upon receiving new syntactic input. The most likely conclusion from this work is that, even if a short purely syntactic initial parsing stage exists, it is relatively inconsequential. A more fruitful research strategy is predicated on the assumption that syntactic and non-syntactic factors can operate concurrently and determine parsing preferences in mutual interaction, with garden-paths and reanalysis as possible outcomes (cf., McClelland, 1987; MacDonald, Pearlmutter & Seidenberg, 1994; Tanenhaus & Trueswell, 1995).

(7a) *The horse raced past the barn fell.* (Bever, 1970)

(7b) *The boat floated down the river sank.*

(7c) *The land mine buried in the sand exploded.*

(7d) *The cop arrested by the detective was guilty of taking bribes.* (McRae et al., 1997)

(7e) *The crook arrested by the detective was guilty of taking bribes.*

The famous Main Clause versus Reduced Relative Clause (MC/RRC) ambiguity exemplified in (7) serves to illustrate the kinds of syntactic and extrasyntactic factors that are thought to steer the course of the sentence parsing process. The first item on the list below represents an elaborate system of syntactic processing strategies worked out by Frazier and her associates (see Frazier & Fodor, 1978; Frazier & Clifton, 1996). Items 2 through 5 have recently been used in a model simulation study by McRae, Spivey-Knowlton & Tanenhaus, (in press). I refer to these publications for discussions of, and pointers to, the supporting experimental literature.

1. *Parsing principles*. One of the key processing strategies proposed by Frazier is called Minimal Attachment. While attempting to integrate new input into the current syntactic tree, the processor initially prefers the attachment with the smallest number of syntactic nodes. Within the grammatical formalism underlying Frazier's model, this is the analysis where the ambiguous verb (*raced, floated*) is finite verb in the main clause. Another important principle is Late Closure (see below).
2. *Thematic fit*. In terms of (7d/e), crooks are more likely to play the thematic role of patient in an arrest event than that of agent.
3. *Relative morphological frequency*. Certain ambiguous verb forms (including *raced* and *floated*) are more frequently used as past-tense main verbs, others as past participles.
4. *Bigram frequency*. The string Verb+*ed* followed by the preposition *by* supports the passive RRC construction.
5. *Configurational bias*. The first NP + finite-verb string in a sentence is preferably interpreted as opening a main clause.
6. *Relative frequency of argument structure (lexical frame)*. Verbs like *race* and *float* are more frequently used as intransitive verbs (lacking a direct object argument) than as transitive verbs (Trueswell, 1996).
7. *Referential ambiguity*. A referentially ambiguous discourse context tends to bias the parser toward an analysis that resolves the ambiguity. For instance, a RRC analysis of *raced past the barn* or *floated down the river* may help to determine a unique referent for *the horse* or *the boat* in a context of several horses or boats (Crain & Steedman, 1985; Altmann & Steedman, 1988).
8. *Syntactic priming*. When two or more exemplars of a problematic grammatical construction, e.g., a garden-path, occur in close temporal succession, the parsing process tends to become progressively easier (see experimental demonstrations by Frazier, Taft, Roeper, Clifton & Ehrlich, 1984, and by Branigan, Pickering, Liversedge, Stewart & Urbach, 1995).

*Reanalysis*. When the parser hits upon information signaling that the current string has been misparsed, reanalysis will be attempted. However, very little is known about the parser's diagnostic and recovery strategies, about the time course of the structure revision process and about the resources it consumes (see Mitchell, 1994, and Gorrell, 1995, for some discussion). Frazier & Rayner (1982), in a pioneering study, explored

eye-movements as cues to the reanalysis process. Friederici (1997; see also her chapter in this volume) presents electrophysiological data relevant to reanalysis.

An important class of hypotheses relates the difficulty of recovery from a misparse to certain configurational similarities between the original and the revised structure. Consider the examples in (8), and assume—in line with most two-stage parsing models—that the parser produces no more than one analysis at a time.

(8a) *Ian knew the answer to the problem was complex.* (Gorrell, 1995)

(8b) *As soon as he had phoned his wife started to prepare for the journey.*  
(Mitchell, 1994)

The second NP in (8a) is initially attached as the direct object of *knew*. This decision follows from the parsing principle of Late Closure, telling the parser to attach new input to the most recently posited clause or phrase (if allowed by the grammar), rather than opening a new phrase or clause. However, application of this heuristic in (8a) precludes the subsequent integration of finite verb *was*. The solution involves three steps:

- (a) de-attaching the direct object NP
- (b) positing a complement clause (with *was* as its finite verb), and
- (c) reattaching the NP as subject of the new clause.

Reanalysis of (8b) proceeds along similar lines:

- (a') de-attaching the direct object NP
- (b') positing a *main* clause (with *started* as its finite verb), and
- (c') reattaching the NP as subject of the new clause.

However, the second step contains a critical difference. In case of (8a), the dominance relationships between the leftmost verb (*knew/phoned*) and the problematic NP are left intact: *knew* dominates this NP both before and after the revision, but *phoned* does so only before the revision. (For precise definitions of 'dominates', see Gorrell, 1995, and Pritchett, 1992.) Formal and informal empirical evidence indeed confirms that (8b) typically causes a boggle effect ('conscious garden-path') whereas the reanalysis in (8a) often goes unnoticed<sup>5</sup>.

### 7.3.3 Aphasic Parsing Deficits

A source of syntactic processing evidence outside the normal range is provided by the comprehension performance of *aphasic* patients, in particular those affected by agrammatism (see also Friederici, this volume). Caplan, Baker & Dehaut (1985; see

<sup>5</sup> Within the framework of a bounded-parallelism parser one might postulate, alternatively, that both analyses are made concurrently in case of (8a), but not of (8b). However, this assumption has to be justified as well.

also Caplan & Hildebrandt, 1988) present the data of an extensive study of sentence comprehension in a large group of aphasics. The patients were presented with spoken sentences of varying grammatical make-up and had to show their understanding by manipulating toy animals (enacting the thematic role assigned to each of the animals). Table I shows examples of the nine sentence types and the percentages of correct understanding.

Computational models of sentence parsing developed for normal language users should be able to simulate data like these by tuning some of their parameters. Two models have recently taken up this challenge: CC-READER (Haarmann, Just & Carpenter, in press) and the Unification Space (Vosse & Kempen, submitted). Both simulations yielded rank correlations of over .90 between the observed scores and the output parameter in the models. This result was obtained, in both cases, by artificially lowering the parser's working memory capacity. This suggests that a similarly adapted version of Gibson's (1997) SPLT model should give at least an equally satisfactory fit with the data in Table I. Even better approximations may be possible when the models take additional factors into account, e.g., frequency differences between active and passive verbs.

**Table I.** Examples of stimulus sentences and comprehension scores in the Caplan, Baker & Dehaut (1985) study. The sentences were taken from Table 1 in Caplan et al.: the numerical data are percentages correct, averaged over the three sets of data reported in Tables 3, 9, and

A	Active	<i>The elephant hit the monkey</i>	81.9
CS	Cleft-subject	<i>It was the elephant that hit the monkey</i>	80.2
P	Passive	<i>The elephant was hit by the monkey</i>	59.2
D	Dative	<i>The elephant gave the monkey to the rabbit</i>	58.7
CO	Cleft-object	<i>It was the elephant that the monkey hit</i>	51.1
C	Conjoined	<i>The elephant hit the monkey and hugged the rabbit</i>	45.0
OS	Object-subject relative	<i>The elephant hit the monkey that hugged the rabbit</i>	41.4
DP	Dative Passive	<i>The elephant was given to the monkey by the rabbit</i>	37.7
SO	Subject-object relative	<i>The elephant that the monkey hit hugged the rabbit</i>	25.9

#### 7.4 Unresolved Cross-Linguistic Issues

After repeatedly having touched on the major HSP debate in the literature—between two-stage (syntax-first, garden-path) models and single-stage (interactive, constraint-satisfaction) models—I now turn to two more fine-grained and as yet undecided issues where cross-linguistic comparisons figure prominently.

*Head-driven parsing strategies.* Many grammatical formalisms assume that word groups or phrases derive their identity from one of its members, called the head. For

example, in noun phrases a noun or pronoun functions as head; prepositional phrases are headed by a preposition, and clauses by main verbs. Other members of those phrases—e.g., determiners and modifiers of NPs, direct and indirect objects in clauses—are supposed to be somehow dependent on their head. Several parsing models, beginning with those developed by Abney (1989) and Pritchett (1991), assign a prominent role to heads of phrases in the parser's processing strategies. More specifically, they postulate parsing principles which cause the attachment of novel input to be postponed until a suitable head has been processed. For instance, an NP that could play the role of direct object in a clause, is left unattached until a transitive verb is seen at an appropriate position in the string. This principle does not delay attachment as long as the NP comes after such a verb; but in verb-final clauses—e.g., in German, Dutch and Japanese—the NP will dangle for a while. On the additional assumption that dangling phrases consume more computational resources than integrated ones, a head-driven parser is predicted to incur a processing problem at the direct object position in verb-final clauses. Quite a few experiments have been conducted in order to test predictions along these lines (e.g., Bader & Lasser, 1994; Konieczny, Hemforth, Scheepers & Strube, 1997). Although the results disconfirm strictly head-driven parsing models, they are compatible with milder versions (see Konieczny *et al.* for a concrete proposal).

*Exposure-based parsing strategies.* That statistical properties of individual words, including the relative frequencies of alternative readings of ambiguous words, affect the parser, is incontrovertible. This raises the question whether parsing performance is also sensitive to frequency effects of a non-lexical nature. A case in point is the attachment pattern in complex noun phrases such as in (9), which offer several alternative landing sites for the relative clause.

(9) *Someone shot the brother of the actress who was on the balcony.*

Cuetos & Mitchell (1988) observed that native speakers of English tend to attach the relative clause to the nearest noun (*actress*, N2), in agreement with the parsing principle of Late Closure. However, this (weak) preference failed to show up in Spanish readers, who manifested a (rather strong) bias in favor of N1 attachment (with the *brother* being the person on the balcony) when reading the translation equivalent of (9). Meanwhile, this pattern has been confirmed in further experiments, and several additional European languages have been taken into consideration as well. It turns out that the N2 bias in English is an exception; German, Dutch and French go along with the Spanish N1 bias.

An obvious place to look for an explanation of this cross-linguistic difference is the frequency of occurrence of both attachment patterns in the languages studied. If the parser is capable of tuning its processing strategies to the preponderant syntactic patterns, then one expects parsing preferences to mirror usage frequencies. How-

ever, the statistical tuning hypothesis has not met with a great deal of success. Attachment frequencies counted in written and spoken corpora for several languages often contradict human parsing preferences (see Brysbaert, Mitchell & Grondelaers, 1997, for data on Dutch and for a cross-linguistic overview).

An important methodological problem, recognized by the investigators, is that the grain-size' chosen in the corpus analyses may have been suboptimal. For instance, should only occurrences of the preposition *o*/and its translation equivalents be included in the counts? Should animacy or personhood of the referent of N1 and/or N2 be taken into consideration? Tabor, Juliano & Tanenhaus (1997) suggest that connectionist neural networks (in particular so-called Simple Recurrent Nets: see Elman, 1995, and Christiansen & Chater, 1997) may provide a way out of the grain-size problem by virtue of their sophisticated statistical learning capacity. Therefore, despite the disappointing results reported to date, it seems premature to give up the statistical tuning hypothesis.

### 7.5 Some Conclusions and Questions

Three decades of research on human sentence processing have made the psycholinguistic community aware of the multitude of external influences—lexical, morphological, conceptual, referential—to which the syntactic parser is exposed. This enables us, not only to design more accurately targeted experiments, but also to gain a better understanding of the structure building operations going on within the parser, and to develop sentence processing architectures that do justice to the complex causation of parsing performance. Advanced process modeling tools, such as are under construction within 'computational psycholinguistics' (Dijkstra & De Smedt, 1996; Crocker, 1996), will prove indispensable. Other computational techniques are already helping us to collect and analyze large corpora of spontaneously produced language utterances, and to put them through sophisticated pattern discovery algorithms (neural nets, memory-based learning). These recent developments enable us to launch innovative research projects into important but neglected HSP questions such as the following:

- (a) How does the parser deal with ill-formed utterances?
- (b) Which relationships exist between syntactic processing in language comprehension and production?

The liability of the human sentence processor to all sorts of parsing preferences is paralleled by its remarkable robustness—its ability to ignore major construction errors in a grammatical edifice, and to carry on its re-construction effortlessly. This feat seems inexplicable without postulating intimate relationships between sentence parsing and sentence production mechanisms.

## References

- Abney, S.P. (1989). A computational model of human parsing. *Journal of Psycholinguistic Research*, 18, 129-144.
- Altmann, G.T.M. & Steedman, M. (1988). Interaction with context during human sentence processing. *Cognition*, 30, 191-238.
- Bach, E., Brown, C. & Marslen-Wilson, W. (1986). Crossed and nested dependencies in German and Dutch: A psycholinguistic study. *Language and Cognitive Processes*, 4, 249-262.
- Bader, M. & Lasser, I. (1994). German verb-final clauses and sentence processing: Evidence for immediate attachment. In C. Clifton, L. Frazier & K. Rayner (eds.), *Perspectives on sentence processing*. Hillsdale NJ: Erlbaum.
- Bever, T.G. (1970). The cognitive basis for linguistic structures. In J.R. Hayes (ed.), *Cognition and the development of language*. New York: Wiley.
- Branigan, H.P., Pickering, M.J., Liversedge, S.P., Stewart, A.J. & Urbach, T.P. (1995). Syntactic priming: Investigating the mental representation of language. *Journal of Psycholinguistic Research*, 24, 489-506.
- Brysbaert, M., Mitchell, D.C. & Grondelaers, S. (submitted). Cross-linguistic differences in modifier attachment biases: Evidence against Gricean and tuning accounts.
- Caplan, D., Baker, C. & Dehaut, F. (1985). Syntactic determinants of sentence comprehension in aphasia. *Cognition*, 21, 117-175.
- Caplan, D. & Hildebrandt, N. (1988). *Disorders of syntactic comprehension*. Cambridge, MA: MIT Press.
- Christiansen, M.H. & Chater, N. (in press). Connectionist natural language processing: The state of the art. *Cognitive Science*.
- Crain, S. & Steedman, M. (1985). On not being led up the garden path: The use of context by the psychological syntax processor. In D. Dowty, L. Karttunen & A. Zwicky (eds.), *Natural language parsing: Psychological, computational and theoretical perspectives*. Cambridge, UK: Cambridge University Press.

- Crocker, M.W. (1996). *Computational psycholinguistics: An interdisciplinary approach to the study of language*. Dordrecht: Kluwer.
- Cuetos, F. & Mitchell, D.C. (1988). Cross-linguistic differences in parsing: Restrictions on the use of the late closure strategy in Spanish. *Cognition*, 30, 73-105.
- Dijkstra, T. & De Smedt, K. (1996). *Computational psycholinguistics: Symbolic and subsymbolic models of language processing*. London: Taylor & Francis.
- Elman, J.L. (1995). Representation and structure in connectionist models. In G.T.M. Altmann (ed.), *Cognitive models of speech processing: Psycholinguistic and computational perspectives*. Cambridge, MA: MIT Press.
- Fodor, J.A., Bever, T.G. & Garrett, M.F. (1974). *The psychology of language*. New York: McGraw-Hill.
- Frazier, L. & Clifton, C. (1996). *Construal*. Cambridge MA: MIT Press.
- Frazier, L. & Fodor, J.D. (1978). The sausage machine: A new two-stage parsing model. *Cognition*, 6, 291-325.
- Frazier, L. & Rayner, K. (1982). Making and correcting errors during sentence comprehension: Eye movements in the analysis of structurally ambiguous sentences. *Cognitive Psychology*, 14, 178-21.
- Frazier, L., Taft, L., Roeper, T., Clifton C. & Ehrlich, K. (1984). Parallel structure: A source of facilitation in sentence comprehension. *Memory and Cognition*, 12, 421-430.
- Friederici, A.D. (1997). Diagnosis and reanalysis: Two processing steps the brain may differentiate. In J.D. Fodor & F. Ferreira (eds.), *Reanalysis in sentence processing*. Dordrecht: Kluwer.
- Garrod, S.C. & Sanford, A.J. (1994). Resolving sentences in a discourse context: How discourse representation affects language understanding. In M. A. Gernsbacher (ed.), *Handbook of psycholinguistics*. San Diego: Academic Press.
- Gernsbacher, M.A. (1994). *Handbook of psycholinguistics*. San Diego: Academic Press.
- Gibson, E. (1997). Linguistic complexity: Locality of syntactic dependencies. MIT manuscript.
- Gorrell, P. (1995). *Syntax and parsing*. Cambridge, UK: Cambridge University Press.
- Haarmann, H.J., Just, M.A. & Carpenter, P.A. (in press). Aphasic sentence comprehension as a resource deficit: A computational approach. *Brain and Language*.
- Jurafsky, D. (1996). A probabilistic model of lexical and syntactic access and disambiguation. *Cognitive Science*, 20, 137-194.

- Just, M.A. & Carpenter, P.A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review*, 99, 122-149.
- Kaan, E. (1997). *Processing subject-object ambiguities in Dutch*. PhD Thesis, University of Groningen. [Groningen Dissertations in Linguistics 20],
- Kempen, G. (1996). Computational models of syntactic processing in human language comprehension. In T. Dijkstra & K. De Smedt (eds.), *Computational psycholinguistics: Symbolic and subsymbolic models of language processing*. London: Taylor & Francis.
- Kimball, J. (1973). Seven principles of surface structure parsing in natural language. *Cognition*, 2, 15-47.
- Konieczny, L., Hemforth, B., Scheepers, C. & Strube, G. (1997). The role of lexical heads in parsing: Evidence from German. *Language and Cognitive Processes*, 12, 307-348.
- Levelt, W.J.M. (1978). A survey of studies in sentence perception: 1970-1976. In W.J.M. Levelt & G.B. Flores d'Arcais (eds.), *Studies in the perception of language*. Chichester: Wiley.
- MacDonald, M.C., Just, M.A. & Carpenter, P.A. (1992). Working memory constraints on the processing of syntactic ambiguity. *Cognitive Psychology*, 24, 56-98.
- MacDonald, M.C., Pearlmutter, N.J. & Seidenberg, M.S. (1994). Lexical nature of syntactic ambiguity resolution. *Psychological Review*, 101, 676-703.
- Marcus, M.P. (1980). *A theory of syntactic recognition for natural language*. Cambridge, MA: MIT Press.
- Marslen-Wilson, W. (1975). Sentence perception as an interactive parallel process. *Science*, 189, 226-228.
- McClelland, J.L. (1987). The case for interactions in language processing. In M. Coltheart (ed.), *Attention and performance XII: The psychology of reading*. Hove UK: Erlbaum.
- McRae, K., Spivey-Knowlton, M.J. & Tanenhaus, M.K. (in press). Modeling the influence of thematic fit (and other constraints) in on-line sentence comprehension. *Journal of Memory and Language*.
- Miller, G.A. & Isard, S.D. (1964). Some perceptual consequence of linguistic rules. *Journal of Verbal Learning and Verbal Behavior*, 2, 217-228.
- Mitchell, D.C. (1994). Sentence parsing. In M.A. Gernsbacher (ed.), *Handbook of psycholinguistics*. San Diego: Academic Press.
- Pritchett, B.L. (1991). Head position and parsing ambiguity. *Journal of Psycholinguistic Research*, 20, 251-270.

- Pritchett, B.L. (1992). *Grammatical competence and parsing performance*. Chicago: The University of Chicago Press.
- Stolz, W.S. (1967). A study of the ability to decode grammatically novel sentences. *Journal of Verbal Learning and Verbal Behavior*, 6, 867-873.
- Tabor, W., Juliano, C. & Tanenhaus, M.K. (1997). Parsing in a dynamical system: An attractor-based account of the interaction of lexical and structural constraints in sentence processing. *Language and Cognitive Processes*, 12, 211 -271.
- Tanenhaus, M.K. & Trueswell, J.C. (1995). Sentence comprehension. In J.L. Miller & P.D. Eimas (eds.), *Speech language and communication*. San Diego: Academic Press.
- Trueswell, J.C. (1996). The role of lexical frequency in syntactic ambiguity resolution. *Journal of Memory and Language*, 35, 566-585.
- Vosse, Th. & Kempen, G. (submitted). Syntactic processing in human sentence comprehension: An inhibition-based parser with a lexicalized grammar.