

Sentence Processing and Syntactic Theory

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1. Introduction

The study of comprehending language in real-time is a central component of the modern linguistic enterprise. In this chapter we explore some ways in which Chomsky's linguistic work has influenced research on one domain of linguistic performance, sentence processing, over the last half century.

Modern research on sentence processing is a cognitivist discipline: Broadly speaking, most researchers assume that understanding sentences requires constructing (a series of) mental representations. Theories attempt to understand the underlying mental computations or principles involved in the incremental construction of said representations in real time. Insofar as sentence processing presupposes the cognitivist framework, Chomsky's general influence is indisputable: Chomsky was an integral member of the group of researchers that brought about the shift towards cognitivism across the psychological sciences (e.g. Anderson, 1976; Fromkin, 1971; Garrett, 1975; Miller 2003) and he vigorously argued that language could, and should, be studied as a cognitive science.

Chomsky's influence on sentence processing research goes much deeper. In the 1950s Chomsky offered a new vision for linguistic research and syntacticians in particular. The job of syntacticians was to formulate grammars that characterize a native speaker's knowledge of which syntactic representations are well-formed in her native language and which are not. These grammars were supposed to offer both broad and deep explanatory coverage across a wide range of linguistic phenomena using maximally general principles. In response to this charge, work on formal grammars exploded, resulting in a variety of highly articulated formal theories and accounts of linguistic phenomena that had hitherto been neglected or unknown.

Chomsky famously maintained the importance of distinguishing linguistic *competence* from linguistic *performance* (e.g. Chomsky 1965). The grammars that syntacticians formulated were supposed to abstract away from "memory limitations, distractions, shifts of attention and interest, and errors (random or characteristic)..." that affect how one understands actual sentences in real time (Chomsky 1965, p. 3). The fact that competence grammars abstract away from performance considerations might lead to the misconception that grammatical theory is irrelevant to sentence processing research, or that sentence processing research is in turn irrelevant to grammatical theorizing.

In this chapter we hope to disabuse readers of this misconception. We provide some examples of how grammatical theory has been - and continues to be - integral to the study of linguistic performance. We seek to show, that Chomsky's claim in *Aspects of the Theory of Syntax* is largely borne out: "the study of performance will proceed only as far as the study of the underlying competence permits" (Chomsky 1965, p. 8). The moral is that we have won insights into the nature of the parser, its operating principles, and aspects of the larger cognitive architecture in which it is embedded specifically by using grammatical representations as the basis for psycholinguistic theorizing: Grammars specify the representations and relations that should (ideally) be computed by the parser. Only when we have a theory of *what* the parser computes, can we generate and evaluate substantive hypotheses about (*whether* and) *how* it is actually computed.

Before proceeding further we must briefly address a question about the scope of modern sentence processing research and its relationship to specific grammatical formalisms. It is not uncommon for researchers (especially formal linguists and philosophers) to assume that a central goal of psycholinguistic research is to validate or falsify particular grammatical analyses.¹ Although psycholinguistic results may, in principle, bear on questions of grammatical formalism, most workaday sentence processing researchers do not see themselves as arbiters of formal linguistic disputes. This is partly for practical reasons: Arguments for or against grammatical formalisms generally turn on very fine-grained representational differences. Unfortunately, our current hypotheses about how to link grammatical representations and operations to parsing algorithms do not allow us to test differences at the desired level of resolution (see, e.g. Phillips & Wagers, 2007; Kush & Dillon, *to appear* for further discussion). Individual grammars are compatible with a wide variety of conceivable processing models.² It is an empirical question which is the right one.

Thus, instead of deciding between one grammatical formalism over another, the day-to-day job of most sentence processing researchers is to pin-down and characterize incremental processing operations at a level that abstracts over very fine-grained grammatical details. The enterprise is thus relatively *formalism-neutral*, but, as we will show below, it is not *theory-neutral*. Grammatical analysis is presupposed. Researchers learn about implementation by investigating phenomena where *all* grammatical formalisms make representational commitments.

In what follows we provide worked-through illustrations of how psycholinguists investigate the algorithmic computation of linguistic representations. It's interesting to note that the three examples we chose to illustrate this are model cases that were foundational in the development of both grammatical theory and psycholinguistic theory alike. We begin by reviewing the literature on incremental ambiguity resolution, move to the processing of long-distance *filler-gap* dependency processing, and conclude with the processing of anaphoric relations. At each point along the way, we will underscore the centrality of grammatical representations in the models considered.

2. Ambiguity Resolution and Reanalysis

We begin with an illustration using perhaps the most-studied phenomenon in sentence processing: ambiguity resolution in so-called “garden path sentences”. Native speakers of English tend to

¹ A well-known example: In the 1960s and 1970s experiments were devised to test the ‘psychological reality’ of Transformational Grammar (TG). Researchers pursued the idea that sentences whose derivation involved more transformations should be more perceptually complex than those whose derivations required fewer transformations. They further assumed that the difference in global perceptual complexity should be visible in a general experimental measure (e.g. whole-sentence reaction times). This hypothesis was the so-called ‘Derivational Theory of Complexity’ (DTC; Chomsky & Miller 1963). Though some early experiments yielded results that appeared compatible with the DTC (e.g., Miller & McKean 1964), later experiments found no correlation between transformational complexity and reaction times (e.g., Slobin 1966). As a result, some researchers rejected the idea of a direct correspondence between grammatical constructs and parsing operations (Fodor, Bever & Garrett 1974; Townsend & Bever 2001), while others rejected transformational grammars in favor of formalisms that were supposedly more ‘directly realizable’ (e.g. Bresnan 1978). There are a number of reasons why these conclusions are unnecessary. Even though the grammatical model that was tested at that time has few modern adherents, it's important to point out that the results do not force rejection of Chomsky (1965) grammar. The version of the DTC that was falsified represented a combination of a formal grammar and specific linking hypotheses (e.g. that the parser executed transformations serially at the end of a sentence *after* deriving the surface structure of the sentence). The results are equally compatible with the conclusion that (one or more of) the linking hypotheses were incorrect, but the grammar was adequate (for an excellent, detailed discussion of these issues see Berwick & Weinberg, 1984, chapter 2).

² To quote Chomsky (1965) on this point:

“...[the] generative grammar does not, in itself, prescribe the character or functioning of a perceptual model...” - Chomsky (1965) p. 9

reject the string in (1) as an ill-formed sentence upon first encountering it. Their intuition is that the verb *stumbled* cannot be integrated with the preceding words.

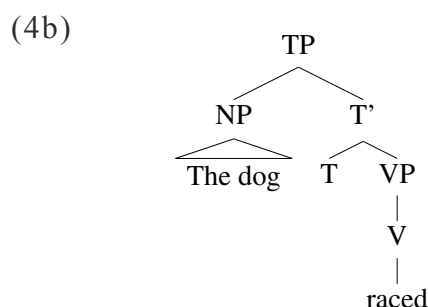
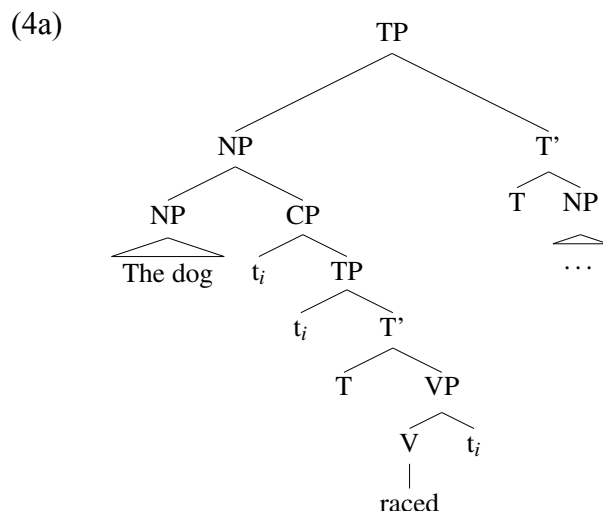
- (1) The dog raced around the track stumbled.

The unacceptability of the sentence is surprising from a purely grammatical perspective. There is a well-formed grammatical analysis for the string under which the substring *the dog raced around the track* should be analyzed as an NP containing a reduced relative clause (henceforth *RedRC*), which is then the subject of *stumbled*. The realization that (1) is, in fact, grammatical can be primed by example. (1) can be analyzed as structurally equivalent to the less difficult (2) and interpreted as synonymous with (3).

- (2) [The dog thrown the ball] stumbled.
 (3) The dog [that was raced around the track] stumbled.

Since the perception of unacceptability is not likely grammatical in origin, we can assume that it arises because parsers fail to analyze the sentence correctly (though cf. McKoon & Ratcliff, 2003). The standard explanation of the effect is as follows. During left-to-right processing the parser encounters a point of *local syntactic ambiguity* at the verb *raced*. The incomplete input is compatible with two divergent syntactic analyses: the RedRC analysis (4a) or a simple main verb analysis (4b). Under (4a) *the dog* is the object of the (passivized) transitive verb *raced*. Under (4b) *the dog* is the subject of the intransitive main verb *raced*. The parser erroneously prefers to pursue the analysis in (4b) and continues down ‘the garden path’ until it reaches *stumbled*, which cannot be grammatically integrated into the representation under construction.

- (4) The dog *raced* ...



Garden path sentences have been used to study (i) the real-time *generation* of grammatical structures, (ii) the implicit *decision processes* that guide selection of an analysis under conditions of uncertainty, and (iii) how closely the incremental representations we generate align with those specified by the grammar. In order to illustrate how the phenomenon has contributed to psycholinguistic theorizing, we start by outlining a well-known model and then consider how other models diverge.

Frazier & Rayner (1982) proposed the *Garden Path* (GP) processing model in which incoming words are incrementally integrated into the developing sentence representation in accordance with grammatical rules. Parsing occurs *serially*: only a single representation can be elaborated at any time. When confronted with local syntactic ambiguity, the parser is forced to commit to one of the analyses. An initial candidate is selected via constituency-based principles. Here the relevant principle was *Minimal Attachment* (see Frazier 1979), which reflects a preference for ‘less complex’ analyses over ‘more complex’ ones. Minimal attachment was proposed not as a heuristic principle in its own right, but as a side-effect of a sentence processing mechanism that attempted to find the first available analysis and take it: Frazier hypothesized that analyses that had more elaborate syntactic structure took more time to compute, and therefore, were unlikely to be selected as the initial parse.

Minimal attachment: Attach incoming material to the phrase-marker being constructed using the fewest nodes consistent with the wellformedness rules of the language under analysis.

According to MA, the parser should prefer (4b) over (4a) because (4b) has fewer nodes.³

The GP model made substantive mentalistic commitments about how ambiguity is handled and the nature of the parser more generally: initial attachment decisions were based on *syntactic complexity*, initial syntactic decisions were *informationally-encapsulated* (in the sense of Fodor 1983), the parser operated serially, and the incremental representations computed by the parser were strictly subject to grammatical wellformedness conditions.

Subsequent models have challenged either one or some combination of these commitments. One strand of recent work in the *Surprisal* framework (Hale 2001; Levy 2008) rejects this approach, choosing to model sentence processors as *rational* agents that make decisions to optimize the probability of success or effectiveness in their environments (Shepard, 1987; Anderson, 1990; Tenenbaum and Griffiths, 2001).⁴ Attachment decisions could be governed by semantic/discourse

³ Note that the MA explanation is compatible, in principle, with *any* formalism under which the constituent structure of (4b) is less complex than (4a).

⁴ It is actually unclear to us whether rational models should be treated as alternatives to implemented incremental process models such as GP theory, or whether rational models simply provide a description of patterns at a higher level of abstraction that eschews questions of implementation.

simplicity biases (e.g. Crain & Steedman 1985)⁵, or by the frequency of the candidate parses (e.g., Hale 2001; Levy 2008). According to frequency-based accounts structures that are encountered more often in every-day language experience are deemed to be more likely to be used in later experience. A number of researchers rejected encapsulation, arguing for models of ambiguity resolution in which attachment decisions simultaneously and probabilistically took multiple information sources into account (e.g., Spivey and Tanenhaus 1998; McRae et al. 1998; Tanenhaus et al., 1995; see also Altmann and Kamide, 1999; Trueswell et al., 1994; MacDonald, 1993). Other models assume that the parser can simultaneously entertain and elaborate multiple analyses *in parallel* (Boston Ferrara, Hale & Vasisht, 2011; Gibson, 1991; Hale, 2001; Stevenson & Merlo, 1997; Tabor & Hutchins, 2004; *i.a.*), perhaps with variable limits on the degree of parallelism (Hale 2014). Preference effects are accounted for by assuming that different parses are *ranked*.

Some accounts of garden-path effects reject the idea (to a greater or lesser degree) that the representations computed by the incremental parser conform to the strictures of the grammar. Bever and Townsend (2001) argued that the initial representations generated by the parser are only indirectly related to grammatical analyses. This approach holds that people first understand sentences by applying heuristic perceptual templates to the input. Difficulty in parsing (1) arises because participants automatically apply a linear template [NP V PP] to the input that maps the first NP to a subject role of the V.

More recent research allows for temporary or small deviations from grammatical well-formedness. Tabor and colleagues have proposed a model in which the structure-generating portion of the parser can temporarily consider analyses that are not wholly consistent with the grammar. Tabor, Galantucci & Richardson (2004) compared how participants processed sentences like those in (5):

- (5) a. The coach smiled at the player *tossed/thrown* a frisbee by...
- b. The coach smiled at the player who was *tossed/thrown* a frisbee by...

The authors asked whether participants encountered more incremental difficulty parsing the RedRC *the player tossed/thrown the frisbee* ...when the verb was *thrown* than *tossed*. *Thrown* is unambiguously a past participle, definitively signalling a RedRC parse. Grammatically, *tossed* must be a past participle heading a RedRC, but *tossed* is form identical to its main verb counterpart. Tabor and colleagues were interested in whether the form of the verb would cause readers to consider the main clause analysis (i.e. treat *the player* as the subject of *tossed a frisbee*) even though the parse was *not locally ambiguous*, per se. The authors found that readers had more difficulty with the RedRC headed by *tossed* than *thrown*. They reasoned that increased difficulty arose because the incorrect parse interfered with the construction of the grammatically acceptable parse. Tabor and colleagues propose that effects can be explained by *self-organizing*

⁵ Crain & Steedman (1985) showed that the referential context can reduce the strength of garden path effects. Intuitively, people seem more likely to adopt the reduced relative clause reading of *the dog raced around the track* if the sentence is preceded by a context that makes the RC necessary to disambiguate.

- (i) There were two dogs cavorting in the yard.
 The dog raced around the track stumbled.

The GP parser would argue that the first-pass parser is just as likely to choose the main clause analysis of *The dog raced* in (i) as in (1), but that this choice would be overridden by referential considerations in stage two.

parsing (SOP) models (Tabor et al. 2004; Tabor & Hutchins 2004) in which words are stored in memory as (grammatically well-formed) tree-fragments that have requirements (e.g. argument structure) that must be met via connection to other treelets. When a word is read, its treelet is activated and begins to establish links with other treelets to satisfy its syntactic or thematic requirements. Treelets can, in principle, establish concurrent bonds with multiple items and the various bonds are weighted according to how compatible they are with the input. The model therefore allows the parser to consider ‘locally coherent’ parses of subsets of the input strings incompatible with the global grammatical analysis. A related theory of sentence processing holds that cue-based memory retrieval is a key component of establishing linguistic dependencies during the course of incremental sentence processing (Lewis & Vasishth, 2005; Lewis, Vasishth, & Van Dyke, 2006; Van Dyke, 2007; Van Dyke & Lewis, 2003). Cue-based memory retrieval involves matching a set of retrieval cues against the contents of working memory to bring previously processed representations back into the focus of attention. This cue-matching process can sometimes lead the parser to retrieve and build dependencies with grammatically inaccessible constituents (Van Dyke, 2007). Thus, like SOP, these models also allow for limited departures from the grammatical ideal as a direct result of the structure-building processes engaged by the parser. Though we do not endorse the model personally, we acknowledge that it represents a substantive hypothesis about the nature of the parser’s structure-generating sub-routines.⁶

Another finding from the garden-path parsing literature has contributed to the debate on representational fidelity. When reading sentences like (6), participants exhibit difficulty at the verb *spit up*.

(6) While Anna dressed the baby spit up on the bed.

The intuitive explanation is that participants first treat *the baby* as the object of *dressed*. Then, when they arrive at *spit up*, it appears as though there is no subject for the main verb. The appropriate parse of the sentence is to treat *dressed* as a reflexive verb and the baby as the main subject. Thus, participants must *revise* their initial parse from (7a) to (7b)

- (7) a. [while Anna dressed the baby], ...
- b. [while Anna dressed], *the baby* ...

In a series of experiments Fernanda Ferreira and colleagues have shown that after reading sentences like (6) interpretations associated with the inaccurate parse persist: If asked whether Anna dressed the baby, participants respond “yes” on a non-negligible number of trials (Christianson et al. 2001, 2006; Ferreira 2003; Ferreira et al. 2001; Swets et al. 2008). The errors were interpreted as evidence that parsers can end up with “good enough” structural representation where *the baby* is both the object of the verb *dressed* and the subject of *spit up*, in violation of the grammar. This intuition was developed into a larger theory of *Good Enough processing* in which parsers heuristically build a ‘rough-and-ready’ parse of the sentence that can deviate from the grammar’s representations (see Sanford & Sturt 2002 for a broader overview of underspecification and shallow processing). An alternate explanation of the effects is possible, under which the parser only builds relations sanctioned by the grammar. Under this second interpretation, structural reanalysis may fail to reliably trigger revision of incremental semantic commitments triggered by earlier parses (e.g. Slattery et al. 2013).

⁶ Some recent work has tried to account for local coherence effects without positing a self-organizing parser (Gibson 2006; Bicknell, Levy & Demberg 2010).

Having sketched models of incremental sentence processing, we should pause to consider what role grammatical representations play in the models above. All but one of the models presuppose that parsers experience difficulty in (1) because they must choose between two *syntactic* representations that more or less conform to the conditions imposed by the competence grammar. Though some models allow for the representations generated by the parser to depart from a strict grammatical template, these departures are constrained. In point of fact, the underlying intuitions of these models can only be articulated in response to the default assumption that representations considered by the parser are those of the grammar.

3. Filler-gap Dependency Processing

In most syntactic theories, argument roles are determined via *local* syntactic relations: *The jerky* is interpreted as a direct object of *chew* in (8) because it is sister to the verb in the syntactic tree.

(8) Loki chewed the jerky.

Even though a reliable position-to-interpretation mapping is possible in simple sentences, natural language is rife with constructions where a strict mapping appears not to work. In the *wh*-question (9a), the sentence-initial phrase *which jerky* is interpreted as the direct object of *chew* as though it occupied the verb's object position (denoted by the gap '___'). Similarly for the head of the relative clause *jerky* in (9b).

- (9) a. Which jerky did Loki chew ___?
b. The jerky that Loki chewed ___ was tough.

Grammatical theories hold that the phrase *which jerky* establishes a dependency with the gap (at some level of representation).⁷ Adopting standard psycholinguistic terminology, we refer to the displaced phrase as the *filler* and the dependencies as *filler-gap dependencies* (FGDs). Within Generative Grammar (starting with Chomsky 1957 and continuing up through Chomsky 1995), the standard analysis maintains a uniform position-to-interpretation mapping by positing that *which jerky* is the sister to the verb *chew* at some level of syntactic representation. The two positions are linked via a transformational operation (*movement*).

Grammatical theories of filler-gap constructions hold that a dependency must be established between a filler and its gap site. Thus, if parsers compute grammatical representations, we expect that the gap site should correspond to a locus of incremental computation: Once the parser recognizes a gap site, processes associated with role assignment can ensue and representations be elaborated. There is substantial evidence that increased computation coincides with gap position during the incremental processing of FGDs (e.g., see the electrophysiological evidence from Kaan et al. 2000; Fiebach et al. 2002; Phillips et al. 2005; Gouvea et al. 2010).

Processing filler-gap dependencies requires managing incremental uncertainty about where a gap will fall in the upcoming sentence. To illustrate: there are multiple (potentially infinite) possible grammatical continuations for the fragment in (10).

⁷ The appropriate grammatical analysis of such constructions has been a matter of debate among competing grammatical formalisms (see Phillips & Wagers 2007 for an accessible overview of different analyses). For ease of exposition we focus on the movement analysis, but all of the psycholinguistic effects that we discuss are compatible with the full range of formal analyses.

- (10) **Which jerky** did Loki ...
- a. ... *chew* ___ behind the couch?
 - b. ... think ___ was behind the couch?
 - c. ... find a place to hide ___ ?
 - d. ... think Tor convinced Jorge that he should *buy* ___?

As with ambiguity resolution, a line of research that deals with exactly how the parser deals with incremental indeterminacy in filler-gap processing has yielded insights into the nature of the parser. Broadly speaking, there are two strategies that a parser might adopt after encountering a filler. It could either passively wait for unambiguous evidence of the true gap position in the sentence, or it could *actively* posit a gap whenever the incomplete string was compatible with a grammatical analysis (Fodor 1978; Frazier 1987). Research provides overwhelming evidence for active gap-filling (AGF). So-called *filled-gap effects* are one type. An example: Stowe (1986) compared incremental reading times between minimally different sentences like (11a) and (11b). In particular, Stowe was interested in whether participants would respond differently to the word *us* in the two sentences.

- (11) My brother wanted to know ...
- a. **who** Ruth will bring **us** home to at Christmas.
 - b. **whether** Ruth will bring **us** home to Mom at Christmas.

Stowe found that readers spent more time reading *us* in (11a) than in (11b). The slowdown is predicted by AGF: if participants pre-emptively committed to a representation that treated *who* as the direct object of *bring* as soon as the verb was encountered, then they should experience difficulty when they read the true direct object *us*, which disconfirms this analysis. The gap-driven model predicts that there should be no such difference because the parser should not eagerly commit to treating *who* as the object of *bring* (see also Crain & Fodor 1985).

One of the most puzzling facts uncovered by research in Generative syntax is the existence of syntactic domains that block filler-gap association, so-called *islands* (Ross 1967; Chomsky 1977). Relative clauses (RCs) are examples of islands: The filler *which jerky* can easily be associated with an object gap after *was chewing* in simple complement clauses (12a), but the same dependency results in unacceptability if *ate* is embedded inside a RC (12b).

- (12) a. *Which book* did Tor say that the happy dog was chewing ___?
 b. **Which book* did Tor say that the dog [that was chewing ___] was happy?

Researchers have used islands to further probe the mechanisms underlying incremental filler-gap processing (e.g., Stowe 1986; Traxler & Pickering 1996; Phillips 2006; Yoshida et al. 2004). For example, some studies test whether the parser ‘blindly’ searches for the first verb in the linear string when attempting to discharge a filler, or whether it is ‘smarter’, choosing only to posit gaps where they would result in acceptable dependencies. In an eye-tracking study Traxler & Pickering (1996) found that signs of AGF were apparent at the verb *wrote* in (13a), but not in (13b) where the verb was embedded inside an island.

- (13) a. The book that the author wrote regularly about ___ was nice.
 b. The book that the author [RC who wrote regularly] reviewed was nice.

Thus, it appears that AGF is ‘suspended’ inside islands. The parser does not operate in such a way that would lead it to temporarily consider FGDs that are judged to be unacceptable offline. The exact reason for why gaps inside islands are unacceptable is still a matter of debate. Some researchers hold that syntactic constraints prohibit FGDs into islands (e.g. Chomsky 1977). As such, the parser could be said to operate in lock-step with the grammar (Phillips 2006). Other frameworks reject a syntactic explanation, opting instead for semantic/pragmatic constraints (Erteschik-Shir 1981; Kuno 1987; Deane 1992, a.o.), frequency effects (Chaves 2013; Hofmeister et al. 2013), or processing/memory explanations (e.g., Kluender & Kutas 1993). We think the evidence against simple memory-limitation accounts is strong (see Sprouse, Wagers & Phillips, 2012a,b). Irrespective of the ultimate correct explanation, psycholinguistic investigation of islands, a phenomenon uncovered by formal grammatical research, has resulted in greater knowledge of the nature of the parser.

Because they require the pairing of distant elements, FGDs make demands on memory. Consequently, examining the processing of FGDs has provided insight into the nature of the memory architecture and systems that subserve sentence processing. We briefly consider one case.

Chomsky & Miller (1963, p. 467) famously discussed cases where memory limitations appear to negatively affect the parser’s ability to compute grammatical FGDs. They noted that it was ‘possible that [the parser] will not contain enough computing space to allow it to understand all sentences in the manner of the [grammar] whose instructions it stores.’ The example most often given to support this observation is doubly center-embedded relative clauses. The sentence in (14) is typically perceived as ill-formed:

(14) The dog that the student that the vet knows loves is kind of a spitfire.

Chomsky & Miller (1963) argued that the perceived unacceptability of (14) should be attributed to short-comings of the parser, and not the grammar, because an independently-motivated simple grammar with recursive rule application could generate a structure for the string in (14). Intuitively, parsing (14) is difficult because it requires simultaneously keeping track of multiple un-integrated fillers before a gap site is encountered. Interestingly, (15) is structurally identical to (14) in all relevant respects, but it is easier to parse (e.g. Gibson & Warren, 2002).

(15) The dog that everyone we know loves is kind of a spitfire.

The acceptability of (15) demonstrates two things. First, insofar as the syntactic structures of (14) and (15) are identical, then (14) is grammatically well-formed. Second, the unacceptability of (14) cannot be linked to the quantity of unintegrated fillers alone. The features of the intervening NPs must be taken into account.

Less well-known is that the properties of the parser can, in fact, lead to spurious amelioration of sentences, leading to so-called ‘grammatical illusions’ in which a sentence sounds acceptable, despite not receiving a licit grammatical analysis (Phillips, Wagers & Lau, 2011). Sticking with the center embedding examples, consider (16):

(16) The dog that the student that Jorge knows is kind of a spitfire.

Astonishingly, (16) often sounds *better* to native English speakers than does (14), despite the fact that it is missing one of the grammatically required verbs and is therefore ungrammatical (Frazier, 1985; Gibson, 1998). This ‘missing V2 effect’ is similarly attributed to memory limitations in the parser, but of a more subtle fashion than the center-embedding ‘crash’ observed in (16). It seems that comprehenders lose track of the number of open subject-verb dependencies when they stack up in memory, and that when they lose track of one of those dependencies, their ability to confirm that it has been grammatically completed is diminished. Parser-grammar disconnects such as these seen in double center-embedding sentences have been influential for psycholinguists attempting to understand the information processing principles that govern language use (see Phillips, Wagers & Lau for a broader discussion of other illusions of grammaticality).

As this brief survey suggests, the study of filler-gap processing has been influential in a range of different areas for psycholinguists: It has informed questions of incremental syntactic analysis, the management of long-distance relationships in working memory during sentence processing, and has yielded insights into apparent disconnects between the parser and the grammar. In this way, grammatical movement operations have been an important model system for both psycholinguists and linguists.

4. Anaphoric Relations

Another area where Chomsky’s research has had an impact on psycholinguistic research is the processing of anaphoric relations. Anaphoric items like reflexives (*himself* in 17a) and pronouns (*him* in 17b) must be linked to antecedents to be fully interpreted. In (17), the reflexive and the pronoun can be co-interpreted with the gender-matching NPs *Tor/Loki* in their respective sentences.

- (17) a. *Tor/Loki* licked *himself_i*.
 b. *Tor/Loki* thought someone would lick *him_i*.

Interestingly, co-interpretation is not always possible. Native speakers have the intuition that *Loki* cannot co-refer with *himself* in (18a) or with *him* in (18b). The sentences in (18) are unacceptable on that interpretation, indicated via co-indexation.

- (18) a. **Loki_k* thought that someone would lick *himself_k*.
 b. *Someone thought that *Loki_k* would lick *him_k*.

Since the 1970s (Reinhart 1976; Lasnik 1976) work in the Generative tradition has tried to explain these facts and worked to formalize constraints that govern the distribution of acceptable antecedents. Chomsky’s (1986) Binding Theory proposed three syntactic principles that governed the interpretation of different types of anaphoric expressions. Principle A stated that reflexive anaphors such as *himself* must have an structurally superior antecedent within their local syntactic domain (e.g. the smallest tensed clause containing the anaphor). Principle B states that non-reflexive pronouns must be free in the same domain. Principle C states that R-expressions (proper names and lexical NPs) cannot be bound. Chomsky’s (1986) BT principles were purely syntactic. Subsequent theoretical work has questioned whether it is best to model these three principles as purely syntactic, with a range of approaches considering semantic, pragmatic and morphological approaches to these constraints (Büring, 2005; Levinson, 1987; Pollard & Sag, 1992; Reinhart & Reuland, 1993; Reinhart, 2006; Roelofsen, 2010; Rooryck & van den Wyngaerd, 2011; Schlenker,

2005). Still, the constraints on interpretation of reflexives, pronouns, and R-expressions have been shown to be empirically robust for canonical examples as in (17/18; Gordon & Hendricks, 1997).⁸

BT has had a substantial indirect influence on sentence processing research because it has played a central role in research that addresses the role that abstract, hierarchical syntactic structure plays in guiding moment-by-moment processing decisions. During incremental processing, participants must identify antecedents for anaphors that they encounter. Many psychological models cast antecedent identification as a memory retrieval process: a pronoun accesses potential candidates from among the broader set of items active in memory (McKoon & Ratcliff 1980; Sanford & Garrod 1982).

Within this tradition many models characterized antecedent identification as a procedure that simultaneously accesses candidates via their morphological features alone (e.g., Sanford & Garrod, 1982). Given restrictions on coreference as in (18), a basic feature-matching model is obviously too simplistic to account for speakers' ultimate coreference judgments. However, it is an empirical question whether such a simple model appropriately characterizes the operations of the processor at some intermediate stage of processing.

Against this background, grammatically-informed psycholinguistic research has probed whether knowledge of grammatical constraints on coreference immediately impact the parser's earliest attempts to identify potential antecedents or how grammatical knowledge interacts with other sources of information. Nicol (1988) used the cross-modal priming technique to investigate what antecedents were reactivated upon processing a reflexive or an anaphor. In cross-modal priming experiments participants are presented with an auditory stimulus that is interrupted by a lexical decision task at key points in the sentence. This technique can be used to evaluate what representations have been covertly activated at a given point in the sentence, by testing to see whether covertly activated representations convey a semantic priming effect on the lexical decision task. Nicol observed evidence that suggested that syntactically local antecedents were reactivated at the point of processing a reflexive, and all antecedents except syntactically local ones were reactivated at the point of processing a direct object pronoun (Nicol & Swinney, 1989). This supported the conclusion that only Binding-compatible antecedents were activated at the point of processing a pronoun/reflexive.

The view that Nicol and Swinney proposed later was dubbed the *Binding-as-initial-filter* hypothesis by Patrick Sturt (2003a, 2003b). Since these early studies, there has been a vigorous debate over the evidence in favor of this view. For example, Badecker and Straub (2002) argued that Nicol and Swinney's experimental paradigm was not sensitive enough to distinguish the *Binding-as-initial-filter* view from the hypothesis that Binding constraints are deployed as one constraint among many on the interpretation of an anaphor (see e.g. Kaiser & Trueswell, 2004). Using self-paced reading, Badecker and Straub (2002) showed that binding inaccessible antecedents interfere with the processing of pronouns and reflexives, which is unexpected if Binding is deployed as a hard filter on interpretations from the earliest get-go. They concluded that the multiple constraints proposal is most likely correct for the processing of pronouns subject to Principle B: Binding theoretic constraints are deployed as one constraint among many on interpretation. This claim remains

⁸ In the psycholinguistic literature, there has been considerable debate over the status of reflexives and anaphors in other syntactic environments (Cunnings & Sturt, 2014; Keller & Asudeh, 2001; Runner, Sussman & Tanenhaus, 2003, 2006).

controversial (Bui & Dillon, 2019; Chow, Lewis & Phillips, 2014; Clifton, Kennison & Albrecht, 1997). For reflexives, Sturt (2003a) showed using eye-tracking-while-reading that Binding Principle A might more appropriately be characterized as a *defeasible* constraint on interpretation. Sturt proposed that there were multiple stages of antecedent evaluation involved in processing a reflexive, and early stages involved the application of Principle A as a filter. In later stages of processing, comprehenders could consult aspects of the discourse, which is perhaps useful for achieving interpretations of reflexives that are not subject to Principle A (so-called *logophoric* interpretations; Sturt, 2003a, 2003b).

Debates over this point are ongoing in the sentence processing literature. The claim that Principle A acts as a hard filter on initial interpretations has seen its share of support (Cunnings & Sturt, 2014; Dillon et al., 2013; Dillon et al., 2014, Dillon, 2014). However, evidence for early interference from non-Principle A accessible antecedents has accumulated, offering support for a range of multiple constraints models that deploy structural and semantic constraints on interpretation in parallel during the processing of reflexive forms (Jaeger, Mertzen, van Dyke & Vasishth, 2019; Parker & Phillips, 2017; Patil, Lewis & Vasishth, 2015; Sloggett, 2017).

Outside of studies investigating the processing of pronouns and reflexives subject to Principles A and B, similar debates have played out in a range of different related contexts. Similar issues about the role of structural and semantic constraints in the analysis of pronouns has played out in research that investigates the processing of bound variable pronouns (Kush, Lidz & Phillips, 2015; Cunnings, Patterson & Felser 2015; Moulton & Han, 2018; Kush & Eik, 2019), readers' ability to access logophoric interpretations for reflexives (Burkhardt, 2002; Foraker, 2003; Runner et al., 2003, 2006; Sloggett, 2017), the processing of crossover constraints in comprehension (Kush et al., 2017), and the processing of name-pronoun relations subject to Binding Principle C (Cowart & Cairns, 1987; van Gompel & Liversedge, 2003; Kazanina et al., 2007; Drummer et al., 2019).

In all of the studies listed above, there is an active, unresolved debate over the degree to which structural principles have priority in settling early interpretive preferences. This sub-literature is a reflection of a broader debate that has characterized the field of sentence processing: does syntactic structure play a privileged role in early sentence analysis, as held by theories such as the Garden Path theory (Frazier & Rayner, 1982), or do comprehenders deploy syntactic and semantic constraints in parallel as they analyze the structure of their linguistic input (e.g. Trueswell et al., 1994)? The brief review above makes it clear that a parallel debate has sprung up around the processing of the Binding Principles: understanding the time course of the application of the binding principles is perhaps the central area where this core architectural question about the human sentence processor is playing out today. Moreover, insofar as the constraints on co-interpretation are ultimately best understood as *structural* in nature, the phenomena above provide a way of probing how incremental parsers encode the abstract linguistic structure necessary to support these inferences during incremental word-by-word processing (Kush, 2013).

Finally, the body of work on anaphor resolution also highlights another way in which Chomsky's work has influenced psycholinguistics. Recall that Chomsky argued that the analysis of linguistic performance would proceed only as far as the study of linguistic competence permits. In the case of this literature, this seems to be true. Nearly all researchers agree that the incremental processing of anaphoric expressions involves direct application of the Binding constraints to constrain interpretation: the role of the grammar in incremental syntactic analysis is not up for serious debate. Instead, the debates in this literature focus on the question of *when* they apply, and *whether* they

have a special prominence in the analysis of anaphoric expressions. In this sense, we see Chomsky's forecast in *Aspects* borne out: the Binding Theory has served as the primary driving force in some of the most active debates on the role of syntactic structure in guiding incremental sentence interpretation in contemporary psycholinguistics.

5 Conclusion

We have shown in these three areas how grammatical analysis has been the basis of psycholinguistic theorizing, and grammatical research has identified important test cases that have led to refinements in our understanding of the parser's real-time operation. Nearly all of this grammatical work can be traced directly or indirectly to the program initiated by Chomsky.

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