CHAPTER 8

SENTENCE COMPREHENSION

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8.1 Introduction

Fluent users of English who encounter the words *dogs, chase*, and *squirrels* in this order will rapidly understand that *dogs* is the agent of the chasing action and the squirrels are chased. The process of converting a linguistic signal into an understanding of a sentence's thematic roles (who did what to whom) is the part of language comprehension that is typically called *sentence processing*. Defined in this way, sentence processing clearly overlaps with many other language comprehension processes, including word recognition, interpretation of prosody, interpretation of pronouns, pragmatics, discourse processes, and many others. Nonetheless, as the existence of this chapter attests, researchers have actively pursued research that is focused on sentence interpretation while at least partially setting aside these related processes, and while recognizing that deriving a thematic interpretation (who did what to whom) is both important and also a waystation on the path to a broader discourse interpretation.

Historically, sentence processing was a distinct field in part because researchers assumed that sentence meaning is recovered from a linear string of words only via generating an explicit syntactic structure or *parse* for the input (Frazier, 1987; Frazier & Clifton, 1996; Frazier & Fodor, 1978; see Vosse & Kempen, 2000, for some parsing history and an alternative lexico-syntactic parsing model). For example, to interpret *Dogs chase squirrels*, Frazier hypothesized that a modular syntactic processor generated a syntactic structure from the grammatical categories of the input (noun, verb, noun), initially without access to word meaning or other context. As with all cognitive processes, the building of syntactic structures can be assumed to be effortful and demanding of memory, which naturally leads to research questions such as whether more complex syntactic structures require more memory. Similarly, researchers can ask how the system confronts the computational burdens of syntactic ambiguity, in which the input is compatible with more than one syntactic structure: are multiple structures built or is one chosen by some metric?

More recently, the notion of obligatory syntactic structure building during sentence processing has come under scrutiny, including by researchers who suggest that sensitivity to words' serial order may supplant at least some hierarchical representations (Christiansen

& Chater, 2001; Frank & Bod, 2011; MacDonald & Christiansen, 2002, cf. Fossum & Levy, 2012), and researchers within several different theoretical frameworks who argue that there is variability across situations (and potentially, across individuals) in the extent to which sentence interpretation is underpinned by construction of a syntactic structure of the input (Ferreira, Bailey, & Ferraro, 2002; Gibson, Bergen, & Piantadosi, 2013; Kuperberg, 2007; Sanford & Sturt, 2002). Despite these reassessments of the necessity of explicit syntactic structure building in interpretation, sentence comprehension remains an active field because the central questions—how perceivers turn a stream of input into an understanding of who did what to whom—have not gone away.

8.2 Measuring sentence processing

Questions concerning the nature of sentence processing are often operationalized as questions about the *difficulty* of sentence comprehension. It is a striking fact that comprehension usually seems effortless, but careful measurements can reveal that some sentences are harder for perceivers to understand than others. An account of these patterns of comprehension ease and difficulty is likely to lead to insight about the underlying comprehension processes. A central tenet of sentence processing research has been that "online" measures of sentence interpretation, collected as a sentence is being perceived, can provide information about comprehension processes that "offline" measures, such as sentence final comprehension questions or judgments of sentence plausibility, cannot (Marslen-Wilson & Tyler, 1975; Tyler & Marslen-Wilson, 1977). Psycholinguists therefore seek tightly time-locked measures of difficulty that can be collected continuously as a sentence is being perceived. These take a number of forms. The most common measures are measures of reading—either eye-tracking (Radach & Kennedy, 2013) or self-paced "moving window" reading in which participants press a key to read each new word of a sentence (Just, Carpenter, & Woolley, 1982). Eye-tracking also offers a behavioral measure of spoken sentence comprehension in "visual world" studies in which comprehenders hear speech while viewing and interacting with a scene (Henderson & Ferreira, 2004; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995; Trueswell & Tanenhaus, 2005). Speed-accuracy tradeoff measures (Foraker & McElree, 2011; McElree, Foraker, & Dyer, 2003) are not quite so continuous but do measure processing at many points in a sentence. Physiological measures of difficulty are continuous and need not require an overt behavioral response during comprehension. These measures include event-related potentials (ERPs) to spoken or written sentences (Kaan, 2007; Kutas & Federmeier, 2011) and magnetoencephalography (MEG) (Dikker, Rabagliati, Farmer, & Pylkkänen, 2010). Other brain-imaging techniques provide information about localization of brain areas involved in language processing, but their timing parameters make them less useful for studies of the time course of comprehension processes (for review, see Osterhout, Kim, & Kuperberg, 2012).

Online assessments of comprehension in the lab are often augmented by one or more other measures. The advent of large speech and text corpora, including ones that are tagged for part of speech and in some cases parsed, allow researchers to examine the relative frequency of alternative words, syntactic structures, lexico-syntax combinations, and other measures that provide estimates of comprehenders' linguistic experiences (Roland, Dick, & Elman, 2007). Another method to estimate the probability of alternative sentence interpretations is to ask participants to rate or complete sentence fragments (McRae, Spivey-Knowlton, & Tanenhaus, 1998; Taraban & McClelland, 1988) and use these offline data to predict online measures such as reading times, thereby providing an estimate of how the probability of alternative interpretations influences comprehension difficulty. The power of large corpora is also harnessed in combinations of these methods—there are now corpora of eye movement data from newspaper reading (Kennedy, Hill, & Pynte, 2003) as well as large-scale normative data about verb-argument usage (for discussion, see Gahl, Jurafsky, & Roland, 2004; Roland & Jurafsky, 2002).

Computational models of sentence processing provide another route to understanding the nature of comprehension processes, via simulating human comprehension performance. Some of these models contain a component that builds an explicit syntactic structure (Vosse & Kempen, 2000, 2009), but most assume that hierarchical-like representations can be learned from more local relationships, provided that the model has an architecture (such as a recurrent network) that can "remember" longer stretches of linguistic input (see Frank & Bod, 2011, for discussion of several architectures). Some of these models are focused on semantic interpretation and thematic role assignment (St. John & McClelland, 1990), but the most common and best known computational models of sentence processing are simple recurrent networks (SRNs), originally developed by Elman (1990).

All of these measures provide insight into sentence comprehension only via a theory's "linking hypothesis" between the empirical data and hypothesized internal processes or computations. As we will see, important developments in the field in recent years have come about via reconsidering linking hypotheses between data and underlying processes. For example, long reading times in certain regions of ambiguous sentences have been variously viewed as reflecting syntactic reanalysis (Frazier & Rayner, 1982), competition or difficulty settling into an interpretation (MacDonald, Pearlmutter, & Seidenberg, 1994), or violation of prediction (Hale, 2001). Similarly, in ERP studies, some researchers have interpreted certain patterns of brain potentials as evidence for syntactic-semantic distinctions (Friederici, 2002), while others see evidence of much more shared processing (Kuperberg, 2007). Michael Tanenhaus has strongly advocated the need for making linking hypotheses more explicit in sentence processing (e.g., Tanenhaus, Magnuson, Dahan, & Chambers, 2000). Following Tanenhaus's advice, we use researchers' linking hypotheses as an organizing principle in discussing alternative models of sentence processing in the next section.

8.3 Sentence processing models

Most research in sentence processing is directed at answering one of two central questions: How do people cope with rampant ambiguity, especially syntactic ambiguity, as the linguistic signal unfolds over time? And how is sentence interpretation affected by variations in syntactic complexity? The hypothesized answers to these questions tend to gather in two broad theoretical approaches: those that emphasize innate processing mechanisms to cope with ambiguity and/or complexity, and those that emphasize the role of prior linguistic experience in sentence interpretation. Many of the theories discussed next appear in Figure 8.1, which arrays the various theoretical approaches on two dimensions. On the

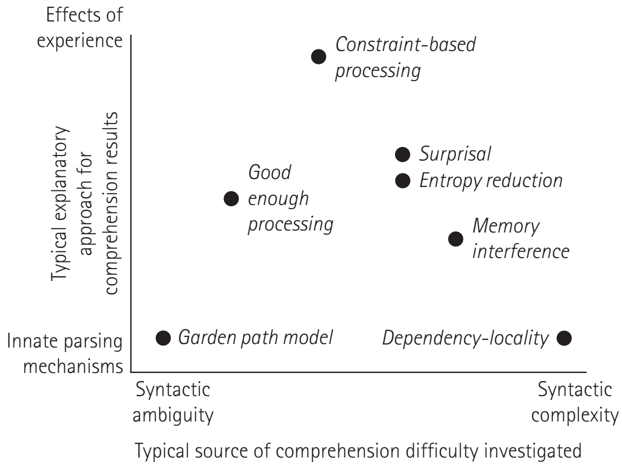

FIG. 8.1 Sentence processing models discussed in this chapter, arranged on two axes indicating the models' general emphasis in explanations for comprehension data and the type of materials most typically studied by proponents of the approach. The axes are meant only to express relative *emphases*, not absolute positions.

x-axis, we show the ambiguity-complexity dimension, indicating the degree to which a given theoretical approach has tended to study comprehension difficulty as a function of ambiguity in the sentence or as a function of syntactic complexity; placement in the middle of this axis reflects an approach that has investigated these two language domains roughly equally. The y-axis shows the general emphasis in explanation for comprehension difficulty. Such emphases are only relative: A theory that emphasizes the role of experience will still assume some innate components and vice versa. The figure is meant to provide a cast of characters for the following discussion and is not meant to capture all ways in which these theories differ, and of course it cannot capture changes in theoretical approaches over time.

One of the striking features in reviewing these models is the proliferation of approaches to the question of what causes comprehension difficulty. In the late twentieth century, the central debate was between modular approaches in which a syntactic parser was initially autonomous from knowledge of word meanings and discourse (Frazier's 1987 Garden Path model) and "constraint-based" accounts (MacDonald, Pearlmutter, & Seidenberg, 1994; Tanenhaus & Trueswell, 1995) and their precursors (Bever, 1970; Marslen-Wilson, 1975), in which syntactic and non-syntactic information richly combine to arrive at an interpretation (for additional sentence processing history, see Sanz, Laka, & Tanenhaus, 2013). Difficulty in the Garden Path model comes not from building an initial syntactic structure but from having to revise it if the initial analysis (which was developed without any access to word meaning or plausibility of alternative interpretations) turns out to be incorrect (Rayner, Carlson, & Frazier, 1983). The constraint-based models have no distinct stages of parsing, semantic interpretation, and reanalysis, and instead emphasize the rapid application of many sources of probabilistic information (Tanenhaus et al., 1995). Difficulty here arises when the probabilistic information conflicts, so that the system cannot "settle" on a single interpretation (MacDonald & Seidenberg, 2006).

Following those debates about modular vs. constraint-based accounts, many more approaches have bloomed. The proliferation of models reflects a typical and healthy progression in science (Preston, 2005), in which new data promote model development. Relatedly, variability in models has emerged in part as a reaction to researchers studying different languages or phenomena that seem to demand different sorts of approaches. For example, Ferreira and colleagues' Good Enough approach to sentence processing (Ferreira et al., 2002; Ferreira & Lowder, 2016; Slattery, Sturt, Christianson, Yoshida, & Ferreira, 2013; Sturt, Sanford, Stewart, & Dawydiak, 2004) focuses less on difficulty of interpretation and emphasizes evidence that incorrect interpretations of ambiguous or complex sentences appear to linger even after a complete syntactic analysis should have ruled them out (see also Christianson, Hollingworth, Halliwell, & Ferreira, 2001).

8.3.1 Innate mechanism vs. experience-driven accounts of ambiguity resolution

Hockett (1954, 1961) discussed how syntactic ambiguities, such as *old men and women*, where it is ambiguous whether this string has a syntactic structure [old [men and women]] in which *old* is modifying both *men* and *women* or the structure [[old men] and [women]] in which *old* modifies only *men* could pose difficulties for comprehenders. He coined the term *garden path* to mean an ambiguous sentence with a very unexpected resolution that gives rise to a conscious feeling of having been led astray. The most famous example in English, owing to Bever (1970), is *The horse raced past the barn fell*, in which it seems initially that the horse is racing, but in fact the meaning is equivalent to *The horse that was raced past the barn fell*. Bever pointed to the importance of lexical information in explaining why this ambiguity led to a garden path, but that claim remained controversial for decades (see discussion in Frazier, 1987; MacDonald et al., 1994; Rayner et al., 1983; Sanz et al., 2013; Trueswell, Tanenhaus, & Garnsey, 1994).

Another example of the contrast between innate and experience-based accounts of comprehension difficulty can be found in a different set of ambiguities (listed 1–3, next). These sentences have a final phrase that could potentially modify, or in syntactic terms, attach to, one of two earlier phrases. A fully ambiguous sentence is given in the (a) versions, and disambiguated versions are in (b–c), with some simplified bracket notation to convey the modification relationships. In the (b) versions, the final phrase modifies a nearby noun or verb, and so is called *local modification* or *low attachment* (because this modified phrase is low in the syntactic structure that the parser generates). The (c) examples show distant modification/high attachment.

1. a. Adverb modification ambiguity: Maria said that her cousins left yesterday.
   b. Local modification: Maria said [that her cousins will leave tomorrow].
   c. Distant modification: Maria will say [that her cousins left] tomorrow.
2. a. Prepositional phrase modification ambiguity: The cat on the rug with black stripes.
   b. Local modification: The cat [on the rug with black tassels].
   c. Distant modification: The cat [on the rug] with black whiskers.

3. a. Relative clause modification ambiguity: The servant of the actress who was on the balcony.
   b. Local modification: The servants [of the actress who was on the balcony].
   c. Distant modification: The servants [of the actress] who were on the balcony.

Although these three kinds of ambiguities have typically been studied separately, they have similar outcomes, at least in English, where comprehenders take longer to read the distant modification (c) sentences compared to the local modification (b) versions (Altmann, van Nice, Garnham, & Henstra, 1998; Cuetos & Mitchell, 1988; MacDonald & Thornton, 2009). Some researchers have explained these patterns with an innate sentence parsing mechanism that causes comprehenders to first attempt to build a syntactic structure in which the ambiguous phrase attaches to the most recent constituent, consistent with the local modification. Several variants of this hypothesis have been developed, the best known of which is the Late Closure principle (Frazier, 1987; for other formulations, see Gibson, Pearlmutter, Canseco-Gonzalez, & Hickok, 1996; Kimball, 1973). An attractive aspect of these approaches is that a single principle makes predictions for a variety of sentence types, and some variants gain additional theoretical mileage by linking this preference for recent constituents to independently established recency effects in memory (Gibson et al., 1996).

However, there is evidence that experience plays a central role in interpretation of these ambiguities. The most telling findings are that the local modification preference varies across languages, as Mitchell and colleagues have shown for the relative clause modification ambiguities as in (3) (Cuetos & Mitchell, 1988; Mitchell, Cuetos, Corley, & Brysbaert, 1995; see Thornton, MacDonald, & Gil, 1999 for cross-linguistic differences in prepositional phrase modification as in (2)). Focusing on the adverb modifications in (1), MacDonald & Thornton (2009) examined how the interpretation preferences could arise from comprehenders' prior experience, in this case the relative frequency of distant vs. local modification interpretations for these structures. Using corpus data (see also Sturt, Costa, Lombardo, & Frasconi, 2003), they found that while local modification interpretations were common in English, distant modification interpretations are rare. They described biases in the production system that promote use of alternative forms to convey the same meaning as a distant modification structure, as in *Maria will say tomorrow that her cousins left* (cf. example 1c). MacDonald and Thornton argued that comprehenders learn from these input patterns to interpret ambiguous modification sentences in favor of the more frequent local modification. Of course, an innate local modification bias and an experience-based approach are not inherently inconsistent, as there could be an innate bias (perhaps owing to a recency advantage in memory, Gibson et al., 1996), and this bias could be modulated by prior experience. However, there is also evidence that in some languages, distant modification is both more frequent and easier than local modification (Mitchell et al., 1995), which suggests that any inherent bias here can be overcome by experience with distant modifications. These results suggest that whatever one's position on innate syntactic processing operations, experience with prior linguistic and non-linguistic input strongly shapes online interpretation of these ambiguous sentences.

8.3.2 Syntactic complexity, memory, and experience

Dating from Miller and Chomsky (Chomsky & Miller, 1963; Miller & Chomsky, 1963), the link between syntactic complexity and comprehension difficulty has been via memory—syntactically more complex sentences are thought to place higher memory burdens on the comprehender, leading to higher comprehension difficulty. The classic contrast involves subject relative (also known as right-branching) clauses, as in (4a), and center-embedded or object relative clauses (4b). In English and most other languages studied to date, subject relatives are more difficult than object relatives (e.g., Gibson, 1998; King & Just, 1991; Traxler et al., 2002; see O'Grady, 2011, for review of some of the cross-linguistic and developmental data). Both syntactic complexity (via memory burdens) and experience explanations have been offered for these patterns.

(4a) Subject Relative: The girl$_i$ [that __$_i$ kissed the woman] was . . .
(4b) Object Relative: The girl$_i$ [that the woman kissed __$_i$] was . . .

Gibson (1998, 2002) hypothesized that memory is taxed when the head of a relative clause (*girl* in 4) must be linked to the "gap" in the relative clause, the position (shown with underlines in 4) where the head is extracted and where the head must be integrated with the verb *kissed*. Gibson's Dependency Locality Theory holds that the memory load to maintain the information of the unresolved dependencies varies with the distance between the head and the gap—longer intervals lead to larger memory burdens, and therefore higher processing difficulty. In (4), information of the head noun must be maintained over more intervening elements in object relatives than in subject relatives, and this additional memory load is hypothesized to be the source of the additional comprehension difficulty.

Another approach emphasizes severe restrictions on the size of working memory so that integration of different parts of a sentence during comprehension relies on rapid retrieval of information from long-term memory (Lewis & Vasishth, 2005; Lewis, Vasishth, & van Dyke, 2006; Martin, 2016; van Dyke & Johns, 2012; van Dyke & McElree, 2006). Sentence components serve as retrieval cues, for example *kissed* in (4) is a cue for retrieving *girl*. This characterization of memory predicts difficulty for long-distance dependencies as in (4), particularly when cues available at retrieval are not easily distinguishable from one another (e.g., *girl* and *woman* in (4b) are semantically similar and both related to *kissed*). Conflicts are alleviated when cues of the antecedents are made highly accessible at retrieval (Fedorenko, Woodbury, & Gibson, 2013). A related similarity-based interference account comes from Gordon and colleagues (Gordon, Hendrick, & Johnson, 2004; Gordon, Hendrick, Johnson, & Lee, 2006), who suggest that interference is lower when the two noun phrases involved in the relative clause are of different grammatical types (e.g., one a full noun and another a pronoun, as in *the girl that you kissed*). It is less clear that similarity-based interference extends to phonological similarity; some studies have found evidence that phonological similarity between sentence nouns or verbs can impair comprehension (Acheson & MacDonald, 2011), while other studies have suggested that phonological interference is not a major factor in comprehension difficulty (Kush, Johns, & van Dyke, 2015). Because phonological form, grammatical category, and meaning are all intercorrelated to some degree (e.g., Dikker et al., 2010), it is likely that similarity-based interference is multifaceted.

An experience-based approach to sentence complexity effects suggests that comprehenders have less experience interpreting syntactically more complex sentences than simpler ones, and that this difference in experience affects comprehension difficulty. Experience-based accounts were initially associated with ambiguity resolution, as just described; because relative clauses were often thought to be unambiguous, experience did not immediately suggest itself as a possible explanation for processing difficulty in relative clauses. More recently, however, ambiguities in relative clauses have been identified in several languages, including English (Gennari & MacDonald, 2008), Mandarin (Y. Hsiao & MacDonald, 2013, 2016; Jäger, Chen, Li, Lin, & Vasishth, 2015), Korean (Kwon, Gordon, Lee, Kluender, & Polinsky, 2010) and Japanese (Miyamoto & Tsujino, 2016). These findings show that that relative clauses cannot be a pure testing ground for effects of syntactic complexity. More generally, information theoretic accounts have noted that there is always uncertainty about upcoming sentence input (Hale, 2006; Levy, 2008), and in that sense we can never set aside ambiguity resolution processes as a potential explanation for comprehension difficulty. On this view, the x-axis in Figure 8.1, rather than being a continuum between ambiguity and complexity, could be seen as a range of different types of ambiguity.

Various types of complex sentences do differ substantially in their frequency and ambiguity in different languages. For example, English object relative clauses like (4b) are less common than subject relatives like (4a) (Roland et al., 2007). They are also more ambiguous: the start of the sentence in *The girl that the woman . . .* might continue as an object relative clause as in (4b) but might instead turn out to be some other structure, such as *The girl that the woman said was leaving/had been kissed by/wanted to give the prize to.* Both frequency and ambiguity affect comprehension difficulty (Gennari & MacDonald, 2008). More generally, much like more widely recognized syntactic ambiguities (MacDonald & Seidenberg, 2006), there is strong lexico-syntactic covariation in relative clauses that affects comprehension ease (Gennari & MacDonald, 2008; Reali, 2014; Reali & Christiansen, 2007; Wiechmann, 2015), meaning that there are ample routes for experience to influence relative clause comprehension.

Mandarin Chinese relative clauses have also been the subject of extensive work concerning their frequency, ambiguity, and memory demands. Mandarin and English relative clauses form an interesting comparison that unconfounds type of relative clause (subject vs. object) and the distance between dependent nouns and verbs: Whereas subject relatives have shorter dependency distance than object relatives in English, subject relatives have longer dependency distances than object relatives in Mandarin. If dependency distance is a key factor in comprehension difficulty, then Mandarin, with its reversed pattern of dependency distance, should also reverse the pattern of difficulty. Some studies have found exactly this reversal, with subject relatives being harder than object relatives (e.g., F. Hsiao & Gibson, 2003), even though subject relatives are more frequent than object relatives in Mandarin. Other studies have cast doubt on these results and have suggested that difficulty is not straightforwardly related to dependency distance. Instead ambiguity in the various relative clauses and comprehenders' experience with these sentences strongly affect comprehension difficulty (Y. Hsiao & MacDonald, 2013, 2016; Jäger et al., 2015; Lin & Bever, 2006). These results suggest that despite the strikingly different structure across Mandarin and English relative clauses, comprehenders' patterns of sensitivity to ambiguity and frequency may not be so different.

The debates between experience- and memory-based accounts are evolving to the point that researchers recognize that both experience and memory constraints will shape processing (Demberg & Keller, 2008; Staub, 2010). That development is a good one, because memory-only or experience-only approaches were never tenable hypotheses, given enormous evidence that readers (and comprehenders more generally) improve with experience, and considering the basic reasons why learning and practice are necessary to become a skilled language user: if computational (working memory) capacity were infinite, every sentence would be trivial to comprehend, and there would be no need to learn from past experience. Instead, comprehension is capacity-constrained, and longer-term learning is necessary to overcome the limitations on processing capacity.

This more ecumenical approach to working memory and experience still leaves numerous issues to investigate, however. A key question is whether the limitations on computational capacity are separable from effects of experience, yielding two independent effects on comprehension difficulty, or whether computational limitations such as attention, retrieval speed from the system's local traffic manager (LTM), and temporary maintenance, are themselves shaped by experience. Dating from Miller's (1956) discussion of chunking, where frequent sequences can be grouped together to form a single "unit" in temporary memory, we have known that experience can expand effective working memory capacity. Perhaps because chunking has often been viewed as reflecting deliberate practice (as in memorizing a telephone number), psycholinguists haven't always considered the extent to which the act of sentence comprehension itself could be expanding capacity, ultimately affecting subsequent sentence processing (though these ideas have long been at the heart of connectionist accounts of language processing, e.g., Elman, 1990; McClelland & Elman, 1986). Several developments suggest that this situation may change. First, there is now active consideration of the role of chunking in comprehension (Christiansen & Chater, 2016, and commentaries), where input is rapidly grouped into larger units—words, phrases, clauses, and so on. All sentence processing theories have assumed that such groupings form a principal component of sentence interpretation, but the explicit use of the term *chunking* may provide a more transparent link between effects of memory and comprehension experience. Second, there is now ample evidence of the effect of experience in sentence processing, as just documented. Third, prior exposure to sequences (regular patterns) also affects the capacity of working memory, even without any attempts to learn sequences or even awareness of them (Botvinick & Bylsma, 2005; G. Jones & Macken, 2015). Specifically, for the relative clauses we have just discussed, computational models and training studies with both natural and artificial languages show how experience with these sentences (MacDonald & Christiansen, 2002; Wells, Christiansen, Race, Acheson, & MacDonald, 2009) and other constructions with long-distance relationships (Amato & MacDonald, 2010; Elman, 1990; Wonnacott, Newport, & Tanenhaus, 2008) can change the effective capacity of a sentence processing network.

A related positive development is a growing consideration of the nature of both working memory and long-term memory retrieval processes in theories of sentence processing. While most comprehension research has drawn on a small number of approaches to working memory (e.g., Baddeley, 1992; Just & Carpenter, 1992), the range of working memory accounts is quite broad in that field, and there is actually significant controversy concerning the nature of verbal working memory, including effects of linguistic experience and other factors with important consequences for language use (Acheson & MacDonald, 2009; Cowan, 2005; Gupta & Tisdale, 2009; D. M. Jones, Macken, & Nicholls, 2004; G. Jones & Macken, 2015; Klem et al., 2015; MacDonald, 2016; MacDonald & Christiansen, 2002). Similarly, the nature of retrieval from long-term memory is a crucial component of interpreting language, but again, there has been relatively little attention to how theories of retrieval must shape models of sentence processing (McElree et al., 2003). Some sentence processing researchers now explicitly identify the memory framework being assumed and interpret comprehension data in that context (Fedorenko, Gibson, & Rohde, 2006; Lewis & Vasishth, 2005; Lewis et al., 2006; MacDonald & Christiansen, 2002; Martin, 2016; Patil, Vasishth, & Lewis, 2016; van Dyke & McElree, 2006). Given the centrality of memory or computational capacity in explanations of difficulty, a precise characterization of memory demands and the role of experience is crucial for any approach to individual differences in comprehension processes (Farmer et al., 2012; MacDonald & Christiansen, 2002; Misyak, Christiansen, & Tomblin, 2010; Prat, 2011; van Dyke, Johns, & Kukona, 2014). There are still significant disagreements here, but the explicit linking of the comprehension and memory work is an important step.

8.3.3 Learning mechanisms, probabilistic models, and computational models

The relationship between memory and sentence processing must incorporate accounts of learning. Encountering language or events in the world entails forming long-term memories (learning), and subsequently using this knowledge to understand language input requires retrieval of what has previously been learned. There are relatively few studies of learning in sentence processing, which is surprising given the centrality of experience in theories of comprehension processes. The focus on adult comprehension of relatively complex sentences means that child language acquisition studies focusing on very simple sentences are of limited use, but there are increasingly studies of comprehension in older children and more complex sentences, which can be integrated with adult research (O'Grady, 2011). Learning can also be studied in adults. Several researchers have used short-term training studies that manipulate people's experience with a natural or artificial language to investigate what can be learned from brief linguistic experience. Many of these studies have found that adults rapidly learn distributional information in their linguistic input, with downstream effects on subsequent sentence comprehension (Amato & MacDonald, 2010; Fine, Jaeger, Farmer, & Qian, 2013; Fraundorf & Jaeger, 2016; Kaschak & Glenberg, 2004; Perek & Goldberg, 2015; Wells et al., 2009; Wonnacott et al., 2008). Researchers have also asked about non-linguistic learning relevant to sentence processing, such as the statistics of events in the world, and the relationship between learning about events in the world and learning about the language that describes them (Altmann & Mirković, 2009; McRae & Matsuki, 2009; Willits, Amato, & MacDonald, 2015). While there has been comparatively little attention to precise learning mechanisms that support language learning and comprehension, studies of the role of sleep in implicit learning of language statistics (e.g., Mirković & Gaskell, 2016) may offer a route to further identify these mechanisms, because sleep processes may be more heavily involved in some kinds of learning than others.

A related learning question concerns the "grains" of learning and the time course of application of this knowledge: each new sentence changes a perceiver's linguistic experience at many levels—the abstract sentence structure, words, intonation contours, the discourse, the co-occurrences of these, and other factors. Which of these experiences yield a measurable change in online sentence processing and final sentence interpretation? Researchers have taken different positions here. Mitchell et al. (1995) argued that for the modification ambiguities like those in (1–3), online measures show evidence only of syntax-level learning (the frequency of alternative structures), independent of words in sentences. The claim of abstract syntactic learning can be linked to findings of syntactic priming in comprehension, in which comprehension of a given sentence type is slightly speeded after prior presentation of the same sentence structure (Kim, Carbary, & Tanenhaus, 2013; Tooley & Traxler, 2010). Since the effect can arise without overlap of words, it can be interpreted as implicit learning and generalization over abstract structures, with consequences for online sentence processing (Chang, Dell, Bock, & Griffin, 2000; Fine & Jaeger, 2013).

Of course, the existence of learning at one level does not exclude learning at other levels, and constraint-based models (or "experience-based accounts") have emphasized the fine-grained nature of learning and the interplay of information at many levels (see Spivey-Knowlton & Sedivy, 1995, for discussion of the modification ambiguities as in (1–3) and MacDonald & Seidenberg, 2006, for review more generally). The notion that so many factors have rapid effects on comprehension has led to objections that constraint-based accounts seem more like a laundry list of factors rather than a theory of sentence parsing mechanisms (Frazier, 1995). Put another way, "It is one thing to suggest that all of these different information sources interact . . . but quite another to specify a psychologically plausible hypothesis about how they interact" (Rumelhart, 1977, p. 588). This point returns us to the multiplicity of theoretical positions in Figure 8.1 and range of phenomena addressed by each, recognizing that every theory emphasizes certain claims and phenomena and sets other issues aside. Researchers approach the question of integrating prior experience in sentence processing in several different ways.

On the one hand, proponents of constraint-based accounts use experiments and computational simulations to focus on learning and weighing of many probabilistic constraints, emphasizing how error-correcting learning algorithms gradually place greater weight on more informative information in the input, leading to increased accuracy of interpretation (Elman, 1990; MacDonald & Christiansen, 2002; Mayberry, Crocker, & Knoeferle, 2009; Tabor & Tanenhaus, 1999). These computational models aim to address online language comprehension but can seem divorced from empirical sentence processing studies with humans, because the models require simplifying assumptions or implementations such as limited vocabulary or impoverished semantics. An alternative is probabilistic accounts in which sentence interpretation proceeds via (unconscious) Bayesian rational inference to choose the most likely interpretation of the current input (see Jurafsky, 2003). Like constraint-based accounts, this approach assumes that abundant probabilistic information is learned from past experience, but the emphasis is different: Compared to constraint-based accounts, the probabilistic models have comparatively less focus on processing mechanisms, emphasizing instead comprehension as rational decision making (Anderson, 1989). Here, the linking hypothesis to comprehension data is via prediction: Bayes' rule, an equation for predicting the probability of input given prior context, provides "a principled and well-understood algorithm for weighing and combining evidence to choose interpretations in comprehension" (Jurafsky, 2003, p. 41). Bayesian accounts such as this are aimed at a computational level of analysis of cognition (Marr, 1982) that characterizes computations necessary for comprehension but without commitments to specific hypothesized processes at Marr's algorithmic level (see Lewis, Howes, & Singh, 2014 for discussion of these levels and intermediate cases). The relative value of Bayesian vs. more algorithmic-level theory development is a point of controversy (e.g., M. Jones & Love, 2011, and commentaries there; see also Jurafsky, 2003, specifically for language processes), but in some respects, the accounts may prove to be very similar (McClelland, 2013). Indeed, several researchers are developing approaches that are intermediate between computational and algorithmic levels, stemming from a consideration of the role of processing capacity in cognitive processes (Griffiths, Lieder, & Goodman, 2015; Lewis et al., 2014). That is, while in principle an infinite amount of data could be considered in making a rational inference, in practice humans' behavior likely reflects a much more restricted range of information. On this *bounded rationality* view (a term initially owing to Simon, 1955), theorizing must consider computational limitations, and attention to this perspective is another example of how theories of memory and computational capacity are central to accounts of sentence interpretation.

8.3.4 Information theoretic approaches

An important development in sentence comprehension is the application of Shannon's (1948) Information Theory to account for comprehension difficulty. This work is generally associated with Bayesian accounts, but as Hale (2016) notes, it is also compatible with other frameworks. Researchers who use this framework to investigate sentence comprehension seek to develop a linking hypothesis between uncertainty, specified by Shannon's original equation or related equations, and human behavior, typically measures of comprehension difficulty such as reading time. Experience is often a factor in calculations of uncertainty, in the sense that prior experience with sequences reduces uncertainty about what is likely upcoming in the linguistic signal, but these approaches do not necessarily commit to particular accounts of learning or sentence processing mechanisms. They are instead working at Marr's (1982) computational level of analysis, aiming to bring the rigor of a mathematical characterization of comprehension behavior to the study of sentence processing, without commitments to specific algorithmic-level processes such as ambiguity resolution or thematic role assignment.

Surprisal and Entropy Reduction are two approaches that make incremental (that is, word by word) predictions about online processing difficulty. A word's surprisal, its negative log probability given a prior context, is a mathematically specified linking hypothesis between comprehension difficulty and behavior such as reading times (Hale, 2001; Levy, 2008; Smith & Levy, 2013). Various formulations of surprisal exist, as researchers may choose different methods to specify the context (e.g., a probabilistic grammar, a corpus; see discussion in Hale, 2016) and a level over which surprisal is calculated, where unlexicalized surprisal is calculated over part of speech (e.g., the probability of a noun given a previous part-of-speech context), or lexicalized surprisal, in which the exact word is predicted from exact word context (Demberg & Keller, 2008; Frank, 2009). These decisions can reflect different theoretical commitments to claims about what "grain" of experience is a primary driver of comprehenders' reading behavior; Demberg and Keller found that unlexicalized surprisal made superior predictions of reading time patterns for English newspaper texts. Frank (2009) observed that an SRN making predictions on upcoming input (Elman, 1990) provides another calculation of surprisal, with better fits to human reading patterns in some types of constructions than at least some other formulations.

An alternative approach, not mutually exclusive with surprisal, is *entropy reduction*, which characterizes uncertainty in a different way (Hale, 2006, 2016). As comprehenders encounter new words in a sentence, these words can disambiguate the prior input; in that they are inconsistent with alternative syntactic parses that were viable earlier in the sentence. Constraining words thus reduce entropy (uncertainty) about upcoming input in the sentence. Words that eliminate many alternative parses and thus strongly reduce entropy are associated with higher comprehension difficulty, reflecting the view that these words require more parsing "work."

8.4 Incrementality, settling, and prediction

In Charles Dickens' *A Christmas Carol*, Ebenezer Scrooge was visited by the ghosts of Christmas Past, Christmas Present, and Christmas Yet to Come. Each one gave Scrooge critical information, which, together with the knowledge that future events were not certain, transformed the lives of Scrooge and other characters. The processes in everyday sentence processing are more prosaic, but they too are controlled by representations of the past, present, and (uncertain) future. The linguistic signal arrives over time, meaning that interpretation processes could be operating at three time scales: (a) interpreting and integrating information that is just arriving into the developing representation of the input; (b) revising or elaborating the representation of past input in light of newly encountered information; and (c) predicting or preparing for future input. All researchers likely believe that these three processes all affect interpretations to some degree, but there has been a significant shift in theorizing over the years concerning the relative emphasis on past, present, and future processing.

8.4.1 Interpreting the present

The term incrementality is used in comprehension to refer to claims that the current input is being interpreted as soon as possible, and to the fullest extent possible. The "as soon as possible" component is seen as necessary to avoid decay of information in memory (see Christiansen & Chater, 2016, for review). Earlier proposals had suggested that processing was delayed until a clause boundary was reached, but these delay approaches faded in the face of evidence for extremely rapid speech processing (see Marslen-Wilson, Tyler, & Seidenberg, 1978). Modular processing perspectives have also implied certain amounts of processing delay, in that they hypothesize restrictions on information flow. For example, the Garden Path model (Frazier, 1987) posited two processing stages, so that syntactic information was processed first, and semantic and discourse information was delayed in its influence. Most accounts of lexical and syntactic interpretation have since done away with rigid processing stages. Instead, the relative time course in which various types of information are brought to bear on interpretation can be seen as a function of how rapidly they can be computed and their informativity (see Brown-Schmidt & Heller in this volume for a review on perspective-taking in incremental sentence comprehension). A useful illustration can be seen in Kawamoto's (1993) connectionist model of lexical ambiguity resolution, in which both bottom-up information and information from prior context exert constraint on the interpretation of the input immediately, and yet the effects of context tend to be weaker and delayed relative to bottom-up information. The bottom-up information tends to be inherently more constraining about the identity of a word, and Kawamoto's simulation illustrates how effects of informativeness can make a continuous process seem to have distinct stages.

8.4.2 Updating the past

The second aspect of incrementality is the degree to which the input is processed to the "fullest extent" possible. Initially controversy about this claim was tied to strictly serial and deterministic accounts, in which a single syntactic structure was adopted for the input, and where building a structure would be a full commitment and failing to build one (or building several, in parallel), would be the absence of commitment. In current probabilistic models, the interpretive mechanisms are thought to be in a probabilistic state, with belief updating as information accrues (Levy, Bicknell, Slattery, & Rayner, 2009). This view is consistent with earlier evidence that downstream context can refine the interpretation of earlier input (Connine & Clifton, 1987; MacDonald, 1994; Warren & Sherman, 1974). There is also good evidence that for both lexical and syntactic ambiguities, this updating does not completely obliterate interpretations that become highly unlikely in the face of new input, such as disambiguating words favoring another interpretation (Barton & Sanford, 1993; Ferreira et al., 2002; Patson, Darowski, Moon, & Ferreira, 2009; Sanford & Sturt, 2002; Slattery et al., 2013).

Indeed, we can ask whether interpretations are ever fully settled. An early example of this idea arose in interpretation of quantifier scope ambiguities, such as in *Every girl climbed a tree*, in which the mapping between girls and trees is uncertain—did every girl climb a different tree, all climb the same tree, or some other mapping? Fodor (1982) suggested that in the absence of strong context that demanded one interpretation, these ambiguities were not necessarily fully resolved. Intuitively, a similar phenomenon happens in interpretation of reference; if we overhear a bit of conversation containing *Tanya didn't say when she would leave*, it is possible to remain in a permanent state of uncertainty about who *Tanya* is or whether *she* refers to *Tanya* or someone else. Probabilistic models (Jurafsky, 2003; Levy et al., 2009) extend these ideas to all ambiguities. This state of affairs represents a contrast with language production, where the utterance plan must be settled by the time of execution, with a choice for one form over another (e.g., implicitly choosing to say *sofa* instead of *couch*).

Noisy channel. One reason why uncertainty about the past persists is that mistakes happen—people do misread or mishear input, and that possibility could shape behavior (Levy et al., 2009). Indeed, the possibility of mistakes and other "noise" in the communicative process (both literal noise and more metaphorical noise, such as inattention, misinterpretation, and so on) could itself be a factor in belief updating about sentence interpretation (Gibson et al., 2013).

8.4.3 Predicting the future

In the same way that there is a degree of uncertainty about the interpretation of prior input, there can be some degree of uncertainty about the nature of upcoming input; this is the sense in which many researchers use terms such as *prediction, expectation*, or *pre-activation* (Altmann & Mirković, 2009; Clark, 2013; Huettig & Mani, 2016; Kuperberg & Jaeger, 2016). Earlier approaches to prediction focused on the degree to which exact words could be predicted; since exact words were predicted very poorly except under very unusual circumstances, researchers were skeptical that prediction could be a major force in comprehension processes (see MacDonald & Seidenberg, 2006). However, prediction is much more than guessing upcoming words: the act of settling into an interpretation for previously encountered input amounts to a prediction that the upcoming input will be consistent with the ongoing probabilities (Kuperberg & Jaeger, 2016; Levy, 2008). Kuperberg and Jaeger also note that updating of the ongoing interpretation is happening at many more levels than the next word; there can be probabilistic predictions for upcoming phonemes, grammatical categories, prosodies, pitches, and many other types of information. The predictions need not be strictly linguistic, and Altmann and Mirković (2009) discuss how sentence comprehension is influenced by predictions over events in the world (e.g., after visits from two ghosts, Scrooge suspected a third was coming). The current focus on prediction in the literature, with a few exceptions (e.g., Ferreira & Lowder, 2016; Huettig & Mani, 2016) ascribes an increasingly important role to prediction, which may be in need of some error correction of its own. That is, brains may indeed be "prediction machines" (Clark, 2013, p. 181), but this does not mean that the central *goal* of the system is prediction. The goal is to interpret the actual input, and prediction is a component of the comprehender's toolkit that aids in that goal. This point is illustrated by a connectionist model developed by Allen and Seidenberg (1999), which was not trained to predict upcoming input but simply to represent the current input. Placed under time pressure, the network began to develop predictions of future input in the service of efficient interpretation of that input when it became the present.

8.5 The relationship between sentence comprehension and production

An important trend in sentence comprehension research is a revised consideration of the relationship between comprehension and production. As Meyer, Huettig, and Levelt (2016) note in their introduction to a special issue of *Journal of Memory and Language* on this topic, comprehension and production processes have traditionally been studied independently, but there are now several research approaches directly investigating the interaction between comprehension and production (see Chapter 20, this volume, for review). One possibility here is in the role of language production in verbal working memory, where some researchers have hypothesized that the maintenance and ordering of verbal information in working memory tasks are accomplished by the language production system, not some dedicated temporary memory store (Acheson & MacDonald, 2009; MacDonald, 2016). On this view, memory that is essential to interpreting language input could also be supported by internal production processes.

Another approach investigates the role of language production in prediction processes. In the previous section, prediction was seen as emergent from comprehension processes settling into an interpretation of the current and past input, but Pickering and Garrod (2007) have argued that the language production system has a central role in prediction during language comprehension. As Dell and Chang (2014) note, prediction of future input on the basis of the semantic representation of prior input is a top down process very like language production, in which a message guides the generation of words for an utterance. The claim here must be that the production system *supports* predictions during comprehension rather than production being the sole route of prediction, because our perceptual systems can generate predictions for actions that we cannot produce, as when we predict the trajectory of a bird's flight.

Prediction via language production can be seen as a specific example of prediction of others' actions more generally, and several groups have suggested that prediction of others' actions emerges from one's own action planning (Pickering & Garrod, 2014; Wolpert, Doya, & Kawato, 2003). Other traditions in joint action research hold that coordinated action, including expectations for others' actions, does not require full prediction via action or language production processes (Vesper, Butterfill, Knoblich, & Sebanz, 2010). Continued work in joint action should be informative about the role of production in comprehension, and this work should also be useful in expanding comprehension research, so often limited to reading texts, to more interactive processes involved in the joint action of conversation.

Another claim for interactions between comprehension and production is the Production, Distribution Comprehension (PDC) account (MacDonald, 1999, 2013), which links comprehension behavior to aspects of the production process over time. The PDC draws on production research to observe that there are typically many viable alternative forms (words, sentences, intonations, and so on) to convey a producer's message. The form that is actually settled on is driven in part by biases toward more easily produced forms, with the consequence that aspects of the language production architecture shape the distribution of sentences that are produced. This distribution in turn shapes comprehenders' linguistic experience, which affects comprehenders' interpretations of ambiguities and complex sentences such as relative clauses (Gennari & MacDonald, 2009; Y. Hsiao & MacDonald, 2016; Humphreys, Mirković, & Gennari, 2016; MacDonald & Thornton, 2009). On this view, if we want to understand comprehension processes via experience and patterns of sentence comprehension difficulty, then we must also address the nature of language production processes, where difficulty of production shapes distribution and ultimately difficulty of comprehension (see commentaries to MacDonald, 2013, for critiques and future directions).

8.6 Sentence processing yet to come

In an analysis of research trends in cognitive science, Cohen Priva and Austerweil (2015) developed models of publishing topics based on 34 years of papers in the journal *Cognition*. Their topics, extracted by a computational model using word patterns in the papers' titles and abstracts, identify some methodological shifts in the journal, such as the rise of eye-tracking methods with the introduction of the visual world paradigm in language comprehension research (Tanenhaus et al., 1995), and they chart interesting changes in how research is framed, with declining references to theories in abstracts, replaced by increasing mention of prior empirical results. The popularity of various research areas has also changed, and one of the most dramatic is "the fall of sentence processing," (p. 4), as evidenced by a sharp decline in articles aligning with the sentence processing topic that the model identified. This trend would seem to be very bad news for the field we have just been reviewing, but we think news of sentence processing's demise is premature, most obviously because it is implausible that a field would be disappearing just as one of its central methodologies (eye-tracking) is soaring. As always, it is important to check the linking hypotheses. Cohen Priva and Austerweil interpret the decline in the "theory" topic as a shift in how authors *frame* their research; the decline of use of words in the "theory" topic is not evidence of theories themselves leaving the pages of *Cognition*. We can apply a similar analysis to the "sentence processing" topic, namely that the field hasn't gone away but is now framed differently, so that the words that cohered to form the original topic (e.g., *sentence, syntactic, verb, structure, language, noun, processing*) no longer are dominant in the titles and abstracts of publications that are focused on the central themes of sentence comprehension identified in this chapter. The decline of specific topic words does likely reflect reduced focus on one theoretical approach: comprehension as requiring an explicit phrase structure during interpretation. We suspect that words capturing some of the other theoretical framings described in this chapter are likely to rise to the fore (e.g., *probabilistic, dependency, expectation, prediction, constraint, information, corpus*, and so on). If so, we could ask whether this different framing reflects different conceptualizations about what sentence processing research seeks to explain. Our impression is that researchers increasingly aim to investigate sentence-level comprehension in connection with other information or constraints, including reference, interactive conversations, event representations, production processes, memory limitations, learning, bilingualism, and others. These areas represent some primary future directions of the field; rather than a decline in sentence processing, we instead see a greater inclusiveness and interaction among comprehension processes.

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