Constraints on sentence comprehension

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The process of comprehending sentences involves the integration of a variety of different information sources, constrained by the available computational resources.

This paper surveys the evidence for four types of constraints on sentence comprehension: (1) lexical constraints, (2) contextual constraints, (3) locality-based computational resource constraints, and (4) phrase-level contingent frequency constraints. These four constraints, in combination with grammatical phrase-formation information and prosody, are sufficient to explain how interpretations are constructed for sentences as they are encountered, including complexity effects in unambiguous sentences and interpretation preferences in ambiguous sentences.

The process of understanding a sentence involves computing its meaning by combining the meanings of its individual words. Research in sentence comprehension examines the representations and processes that are needed to connect the identification of individual words in speech or reading with the mapping of sentence meanings onto mental models or discourse representations. We will focus on a specific framework in which all the constraints are determined by a set of interacting informational constraints, constrained by the available computational resources, and written sentence comprehension: (1) lexical, or word-level, constraints, which depend on knowledge associated with particular words in a language; (2) contextual constraints, which involve the communicative utility and the plausibility of different interpretations, given knowledge about the state of the world; (3) computational resource constraints, which depend on the availability of and access to working memory resources; (4) Phrase-level contingent frequency constraints, defined as the probability of phrases occurring in particular phrase structure contexts.

We describe the four kinds of constraints in more detail below, assuming a framework in which all the constraints apply freely. One additional constraint is prosody, which refers to properties of the speech signal beyond those related to the identity of words. These properties include variations in the pitch, amplitude and duration of individual speech sounds, and cross-modal links in spatial attention.
Box 1. The hierarchical structure of sentences

The meaning of a sentence is formed from a combination of the meanings of smaller parts of the sentence called constituents or phrases. The meaning of each phrase is fully determined by a combination of the meanings of its constituents, down to the word level and below. A phrase structure for the sentence: The reporter who the senator attacked defended the report on the web is provided in the Figure, with phrase shown down to the word level. Each phrase contains a particular word-level category, called the head of the phrase, which is obligatorily present in all instances of that phrase type. For example, the head of a verb phrase (VP) is a verb, the head of a noun phrase (NP) is a noun, etc. Thus, the head of the NP the reporter is the noun reporter and the head of the VP defended the report on the web is the verb defended. All other categories are dependents of the head of the phrase that immediately dominates them. For example, the article the is a dependent of the noun reporter in the VP defended the report. The NP the reporter and the prepositional phrase on the web are dependents of the verb defended in the phrase structure shown.

The sentence (S) in the Figure is composed of two phrases at the top level of analysis (1) an NP, the reporter who the senator attacked and (2) a VP, defended the report on the web. This initial NP is referred to as the subject of the verb defended, and it is interpreted as the individual performing the action specified by the verb. The VP is further broken down into three constituents: (1) a verb, defended, (2) an NP immediately following the verb (the verb’s object), the reporter, and (3) the PP, on the web. The object NP is interpreted as the element on which the action is performed, and the PP is interpreted as the location where the action takes place. This division represents one of two possible interpretations of the VP, one in which the act of defending the report took place on the web, and the other in which the report was moved to the web. The NP the reporter is divided into two further constituents: an article the and a noun reporter. The PP is also divided into two constituents: a preposition on and an NP the web.

Under a second interpretation of the VP, the report was on the web, and the reporter defended this report using an unstated medium (speaking, perhaps). The constituent structure for this alternative interpretation of the VP would consist of a verb and an NP, with the NP being further subdivided into an NP the reporter and the PP on the web. There is said to be an attachment ambiguity at this point of processing the PP on the web: the PP can either attach as part of the VP defended the report, or as part of the NP the reporter issued by the report. The subject NP the reporter who the senator attacked is subdivided into two constituents: a simple NP the reporter and a relative clause (RC) who the senator attacked, which is a sentence modifier (S’) for the NP. The S’ is further subdivided into a relative pronoun (Rel-pro) who, which refers to the NP the reporter; and an S the senator attacked. The co-reference between the relative pronoun who and the NP the reporter is indicated by the subscripted i on each.

Within the RC, the relative pronoun who is referred to as a filler and is interpreted as the entity which is acted on by the verb attacked. This relationship is identified in the phrase structure by the presence of a co-indexed empty element i (a gap) in the object position of the VP.

Note that, although most of the phrase-structure hypotheses implicit here are standard across most syntactic and semantic theories, some of the assumptions that we make are less universally accepted. For example, the inventory of categories and their relationship to one another are definable14,15, as is the implicit claim that there exist empty-category positions mediating long-distance dependencies16. The specific assumptions that we make with respect to these controversial issues are for convenience only, so that we have a consistent notation to discuss sentence meaning.

References


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the effect of additional word-level properties has been considered\(^{28}\). However, the variety and importance of such constraints in immediate moment-to-moment interpretation has been demonstrated only recently, in studies examining temporarily ambiguous sentences. One such type of ambiguous sentence is shown in (1).

\[(1) \text{ Amanda believed the senator…} \]

(a) … during the speech.

(b) … was lying to the committee.

In (1), the relationship between the phrase the senator and the rest of the sentence is temporarily ambiguous if the sentence continues as in (1a), then it is the senator who Amanda believes. If instead the sentence continues as in (1b), then the senator turns out to be the subject of the embedded sentence the senator was lying to the committee.

The ambiguity arises because verbs like believed can license an object noun phrase (NP) \([\text{the interpretation forced in (1a)}]\) or an embedded sentence \([\text{forced in (1b)}]\), and either possibility is acceptable prior to encountering one of the endings. Furthermore, the ambiguous region can be lengthened considerably (e.g. Amanda believed the senator from the glorious Commonwealth of Massachusetts was lying…), and thus the sentence processor must make some decision about a preferred interpretation during the ambiguous region. One way of making a decision about how to interpret the ambiguous is to make use of some detailed information associated with the verb believed: in addition to knowing that it permits either an object NP or an embedded sentence, comprehenders might keep track of the relative frequency of these alternatives\(^{22,23}\). The relative frequency can be determined by having subjects write whole-sentence completions for fragments like Amanda believed….

\[^{22,23}\text{Believed is used more than three times as often with an embedded sentence (e.g. (1b)) as with an object NP (e.g. (1a)), and thus if the sentence comprehension mechanism relies on this kind of information, it will tend to prefer the embedded sentence alternative for the verb believed. Verbs with relative frequencies favoring the object NP alternative (e.g. understood, which licenses an object NP roughly eight times more often than an embedded sentence) would create the opposite preference – in favor of the object NP alternative. Comprehenders are sensitive to these relative frequencies, showing little or no difficulty in reading continuations like (1b) when the verb licensing the ambiguity more often takes an embedded sentence (e.g. believed), but showing substantial difficulty when the verb licensing the ambiguity more often occurs with an object NP (e.g. understood)\]^{22,23}.

Similar lexically-based frequency constraints have been shown to influence preferences in a variety of other ambiguities as well, examples of which are shown in (2) and (3). In (2), the verb examined can be the head of the main verb phrase (VP) of the sentence, as is required by (2a), but instead might initiate a relative clause modifying the defendant, as in (2b), where the main VP is had always declared….

\[(2) \text{ The defendant examined…} \]

(a) … the confession and then declared his innocence.

(b) … the lawyer had always declared his innocence.

In (3), the prepositional phrase (PP) with the binoculars can modify the seeing event (so that the spy is using them), but it might instead modify the cop (so that the cop has the binoculars rather than the spy). Preferences in this ambiguity have been argued to depend on the verb’s preference to take PPs headed by particular prepositions as arguments\(^{26}\), as well as the noun’s preference to take a PP or an object NP, with the objective PP preference to assign the particular interpretation required in each alternative\(^{27,28}\).

\[(3) \text{ The spy saw the cop with the binoculars.} \]

**Contextual constraints**

In addition to constraints associated with specific lexical representations, information that can be computed from the sentence or from the discourse context can also immediately influence sentence comprehension. This is particularly apparent in ambiguity resolution, where a variety of studies have examined the effects of contextual influences such as plausibility and referential complexity.

In the case of plausibility, most studies have examined the effect of making one alternative for an ambiguity implausible, typically by manipulating the semantic relationships between verbs and their arguments within a clause or sentence. For example, (4) contains the same temporary ambiguity as (2). The implausibility of evidence examining something leads to a preference for the relative clause interpretation\(^{29}\).

\[(4) \text{ The evidence examined by the lawyer had always been considered circumstantial.} \]

Plausibility influences in comprehension have also been shown with respect to the object NP versus embedded sentence ambiguity in (1) \([\text{Ref. 25}]\), the PP attachment ambiguity in (3) \([\text{Ref. 31}]\), the gerund/present-participle ambiguity in (4) \([\text{Ref. 32}]\), and filler–gap ambiguities \([\text{Ref. 33}]\).

\[(5) \text{ Visiting relatives…} \]

(a) … are fun.

(b) … is fun.

Referential contexts have also been shown to influence many of the same ambiguities, in situations in which the alternatives require reference to single versus multiple referents. For example, modification of a noun by a relative clause (RC) or PP typically involves a presupposition that the noun has multiple referents in the discourse, from which the RC or PP selects. Thus in the ambiguity in (2), the RC alternative (2b) requires a presupposition that the matrix VP alternative (2a) does not, making the RC alternative illicitious. However, if the prior discourse context contains the presupposed multiple referents, the RC alternative may be preferred\(^{30,31}\).
Referential context effects have also been demonstrated for PP attachment using preceding linguistic context and using concurrent visual context. In the latter case, for example, comprehenders heard the instruction in (6), which contains a temporary ambiguity involving the attachment of the PP on the towel.

(6) Put the apple on the towel in the box.

The participants in the experiment showed no difficulty in interpreting the ambiguity correctly when the instruction was presented concurrently with a display containing two referents for apple, one on a towel and one on a napkin. When only a single referent was visible, however, they had significantly more difficulty interpreting the instruction.

Computational resource constraints: locality

An important constraint affecting sentence comprehension, which is not reducible to lexical or contextual constraints, is locality. In ambiguous structures, the locality constraint causes a preference for an interpretation associated with a local attachment over an interpretation associated with a less local attachment. For example, locality explains the existence of the strongly preferred interpretation of (7), in which the adverbial yesterday is associated to the clause the suspect left the country, rather than to the clause headed by told.

(7) The bartender told the detective that the suspect left the country yesterday.

In addition to its application in ambiguity resolution, locality is also an important factor in determining the processing difficulty of unambiguous structures. For example, in English, a relative clause (RC) whose relative pronoun is coindexed with a gap in object position, as in (8a), is more complex than a variety of measures than a relative clause whose relative pronoun is coindexed with a gap in subject position, as in (8b) (Refs 41-43). Furthermore, aphasics and stroke patients cannot reliably answer comprehension questions about object-RCs, although they perform well on subject-RCs (Ref. 44).

(8a) The reporter, who, the senator attached $e$, admitted the error.

(8b) The reporter, who, $e$, attached the senator admitted the error.

This difference can be explained by locality considerations: the distance between the relative pronoun who and the gap $e$ is longer with an object-gap, where the NP the senator intervenes, than with a subject-gap, where the two are adjacent. According to one recent theory, locality constrains two central components of sentence comprehension: first, structural integration, consisting of integrating new input words into the currently existing syntactic and discourse structures; and secondly, storage of the syntactic categories that are necessary to complete the current input string as a grammatical sentence. Locality constrains these components as follows: (1) the greater the distance between an incoming word and the head or dependent to which it attaches, the greater the integration cost; and (2) the longer a predicted category must be kept in memory before being encountered, the greater is the cost for maintaining that prediction. Under this theory, locality is computed in terms of new discourse reference phrases representing objects and events in the world that can later be referred to using a referential expression, such as a pronoun. Locality accounts for preferences in ambiguous attachment structures such as (7) under the assumption that the sentence comprehension mechanism attempts to minimize the integration cost at each step: integrating yesterday to the VP headed by told involves crossing structures for the intervening material that the suspect left the country, whereas integrating yesterday to the VP headed by left involves crossing only the NP the country.

The severe complexity of nested structures is also explained by locality. A syntactic category A is said to be nested within another category B if B contains A, a constituent to the left of A, and a constituent to the right of A. The difficulty of processing nested clauses is illustrated in (9):

(9) (a) The scientist collaborated with the professor who, $e$, had advised the student [who $e$, copied the article].

(b) (The student [who, the professor] [who, the scientist collaborated with $e$] had advised $e$, copied the article).

Sentence (9a) contains no nested clauses and is relatively easy to understand. On the other hand, in (9b), the relative clause who the scientist collaborated with is nested within the embedded clause the professor... had advised, and this clause is nested within the outer clause the student... copied the article. The doubly nested structure of (9b) makes this sentence very difficult to understand.

According to the locality-based proposal, the processing difficulty associated with nested structures has to do with the distance between heads and their dependents. In non-nested structures, heads are close to their dependents, often adjacent to one another, whereas some heads and dependents are widely separated in nested structures. For example, in the non-nested structure in (9a), the relative pronouns and their associated gaps are adjacent. In contrast, the relative pronouns and their associated gaps are adjacent in the nested structure in (9b), especially for the outer pair. This difference in head-dependent distance leads to both integration and memory cost differences in the processing of these two structures.

Interestingly, doubly-nested structures like (9b) are easier to understand when a first- or second-person pronoun is in the subject position of the outer RC and a constituent to the right of the pronoun. The discourse-based computation of locality explains this result. Because all discourses implicitly include a speaker/listener and a first- or second-person pronoun, all discourse spans are said to refer to every discourse. Thus the distance between the relative pronouns and their associated gaps is less when I replaces the scientist in (9b), and the structure is correspondingly less complex. Complexity rating experiments across a range of nested constructions in different languages support the predictions of the locality-based theory.

The memory cost component of the theory also provides an account of comprehension effects involving locally ambiguous filler-gap dependencies. It has been observed...
in a variety of languages that, given a filler, people prefer to posit a gap for the filler as soon as possible\(^{69a,69b}\)). This preference is attributed to the memory cost component of the theory, by positing a gap as soon as possible, the processor minimizes the number of syntactic predictions that it needs to store. In addition, the position in which a gap is posited is modulated by plausibility as well as the lexical properties of the licensing head (e.g. a verb\(^{39}\)).

Locality in ambiguity resolution interacts with a second factor. This can be seen in the processing of Spanish sentences like (10) below.

\[(10) \text{El astrónomo predijo la órbita del planeta [que se observó desde el satélite].} \]  
(The astronomer predicted the orbit of the planet [that was observed from the satellite].)

Spanish comprehenders read the relative clause que se observó desde el satélite more quickly when it is disambiguated towards the non-local site órbita than when it is disambiguated towards the local site planeta (E. Gibson, N. Pearlmutter and V. Torrens, unpublished data), thus demonstrating an anti-locality bias in this construction. One account of this result is that a second factor competes with locality, predicate proximity, which favors attachments that are structurally closer to verbs\(^{40}\). Because órbita is structurally closer to a verb (predijo) than planeta, predicate proximity competes with locality in this construction, and predicate proximity wins. An alternative proposal for the second factor is one that favors interpretations in which the relative pronoun in the RC is bound to the most salient available antecedent in the discourse: the first NP in these examples\(^{41}\). Evidence for the two-factors hypothesis comes from the construction in (11), which is formed from (10) by adding a third potential NP attachment site, como (E. Gibson, N. Pearlmutter and V. Torrens, unpublished data):

\[(11) \text{El astrónomo predijo el cambio de la órbita del planeta [que se observó desde el satélite].} \]  
(The astronomer predicted the change of the orbit of the planet [that was observed from the satellite].)

Because attachments to non-local sites become more difficult with increasing distance, locality weighs strongly against the attachment of the RC to the first site como. The higher locality cost outweighs the competing non-local attachment factor, so that local attachment (to planeta) is preferred. Attachment to the first site is the next most likely, because the second factor favors this attachment. Attachment to the intermediate site órbita is not favored by any constraints, and it is correspondingly the most difficult attachment to make (Ref. 40 and E. Gibson, N. Pearlmutter and V. Torrens, unpublished data). Furthermore, locality and the second factor cannot be lexically-based, because both the two- and three-site ambiguities involve the same attaching phrase (a RC) as well as two of the same potential attachment sites immediately preceding it, yet one site is favored in the two-site ambiguity órbita in (10), while the other site is favored in the three-site ambiguity [planeta in (11)].

Interestingly, the non-local attachment preference observed in the Spanish two-site ambiguity in (10) is not universally present across languages. In particular, English displays a local attachment bias in corresponding English items\(^{42}\). To account for the cross-linguistic variability, it has been proposed that the cost associated with violating the non-local attachment factor varies across languages\(^{43,44}\). However, the nature of the factor favoring non-local attachment in these constructions is uncertain, as is the source of these cross-linguistic differences.

**Phrase-level contingent frequency constraints**

An alternative possible explanation of cross-linguistic and cross-structure preference differences relies on keeping track of the frequencies of ambiguity resolutions contingent on different lexical and phrase structure environments\(^{45,46}\). This contingent frequency approach differs from the use of purely lexical constraints in that the frequencies involved are assumed to be tabulated over syntactic constructions rather than individual lexical items (e.g. the NP-Prep-NP-Prep-NP-RC construction in (10), and the NP-Prep-NP-Prep-NP-RC construction in (11)). However, there is evidence that ambiguity resolution frequencies in naturally produced written text do not always match comprehension preferences\(^{47}\). If the
tions that have been analysed thus far are representative of those that people are normally exposed to, then the contingent frequency approach might have difficulty in accounting for such a discrepancy.

The strongest evidence for the need to keep track of contingent frequencies of phrase structures in sentence comprehension is provided by a set of experiments involving the grammatical category ambiguity of the word that\(^{10,11}\). For example, in (12a) and (13a) the word that is a demonstrative article, modifying the noun hotel. In (12b) and (13b) on the other hand, the word that is a comple-

mentizer, introducing an embedded sentence *(cheap beds were clean ...)*.

(12a) That cheap hotel was clean and comfortable in our view.

(12b) That cheap beds were clean and comfortable surprised us.

(13a) The lawyer insisted that cheap hotel was clean and comfortable.

(13b) The lawyer insisted that cheap beds were clean and comfortable.

In sentence-initial contexts like (12), there is a preference to resolve the ambiguity in favor of the article interpretation (12a), whereas in post-verbal contexts like (13), there is a preference to resolve the ambiguity in favor of the comple-

mentizer interpretation (13b) (Refs 56, 57). Keeping track of contingent frequencies is one way to account for these re-

sults, but there are others. In particular, memory resource factors might favor the article interpretation in the sent-

ence-initial plural context\(^2\), but not differentiate the two in the post-verbal context, so that the higher frequency of the complementizer interpretation (lexical frequency inde-

pendent of phrase-level context) could determine the pref-

erence in this environment.

**Conclusion**

We have discussed four types of constraints that are opera-

tive during sentence comprehension: lexical constraints, con-

textual constraints, a locality-based computational resource con-

straint, and phrase-level contingent frequency constraints.\(^2\)

We discussed a variety of evidence for the first three of these constraint, and phrase-level contingent frequency constraints.\(^3\) We have discussed four types of constraints that are opera-

tive during sentence comprehension: lexical constraints, com-

prehensive context and, in speech, prosodic but noted that the status of contingent frequency constraints

**References**


References added in press


