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The Relationship Between Parsing and Generation

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Abstract

Humans use their linguistic knowledge in at least two ways: on the one hand, to convey what they mean to others or to themselves, and on the other hand, to understand what others say or what they themselves say. In either case, they must assemble the syntactic structures of sentences in a systematic fashion, in accordance with the grammar of their language. In this article, we advance the view that a single mechanism for building sentence structure may be sufficient for structure building in comprehension and production. We argue that differing behaviors reduce to differences in the available information in either task. This view has broad implications for the architecture of the human language system and provides a useful framework for integrating largely independent research programs on comprehension and production by both constraining the models and uncovering new questions that can drive further research.

1. INTRODUCTION

Humans use their linguistic knowledge in at least two ways: on one hand, to convey what they mean to others or to themselves, and on the other hand, to understand what others say or what they themselves say. In either case, they must assemble the syntactic structures of sentences in a systematic fashion, in accordance with the grammar of their language. In this review, we discuss the benefits of a single model of structure building for comprehension and production (Section 2), and we synthesize previous proposals (Section 3) and challenges (Section 5) for relating comprehension and production mechanisms. We argue that it is plausible to pursue a single model (Section 4).

To avoid confusion, we should first clarify what we do not intend to argue in this review. We do not claim that the cognitive systems for comprehension and production are identical in their entirety. Such a view would require that the cognitive mechanisms for moving our lips and tongues be involved in comprehension, and that the cognitive mechanisms for analyzing sound waves or visual patterns be critically involved in production. Although related claims are sometimes advanced under the heading of embodied cognition (e.g., Pickering & Garrod 2007, 2013), we remain agnostic about such a view. Thus, despite superficial similarities, our proposal should not be confused with that view, and we do not review the literature on that topic, such as evidence for or against the involvement of motor control mechanisms in sentence comprehension. Our primary concern is whether the syntactic structure-building mechanism of the cognitive mechanisms is shared between comprehension and production. Thus, we use the terms parsing and generation to refer specifically to the structural processes involved in comprehension and production, respectively.

Although our claims are restricted to the identity of structure-building mechanisms in comprehension and production, we maintain that this issue has far-reaching consequences for the architecture of the human language system, as we discuss next.

2. WHY THE PROBLEM IS IMPORTANT

Understanding the relationship between models of parsing and generation is central to the larger project of connecting high-level linguistic theories with psycholinguistic theories. In relating psycholinguistic and linguistic theories, it is important to distinguish three dimensions: tasks, levels of analysis, and mechanisms.

2.1. Tasks

It is clear that we use our linguistic knowledge to carry out a variety of different tasks. When we speak, we start with an intended meaning and try to find an external form that conveys that meaning. When we understand, we start with an external form and try to identify the intended meaning. When we make acceptability judgments, we take a form–meaning pairing and try to determine whether the form and the meaning are connected. All three tasks have a shared subgoal of building a structure that links the form and the meaning. They differ only in what information is provided as a starting point.

2.2. Levels of Analysis

The same cognitive system can be described at multiple levels of analysis. Traditional linguistic theories are theories of mental representations, but they abstract away from details of timing, how those representations are encoded in memory, neural connectivity, and so on. It is common to appeal to the three levels proposed by Marr (1982) for analyses of visual systems, but Marr's levels do not correspond closely to standard practice in linguistics and psycholinguistics. It is probably more accurate to view levels of analysis on a continuum, with as many different levels as there are details that can be abstracted away from or included.

2.3. Mechanisms

The distinctions among tasks and among levels of analysis are necessary, and accounts of speaking, understanding, and acceptability judgments tend to focus on different tasks and on different levels of analysis. But this does not amount to the claim that distinct cognitive mechanisms build the same representations for different tasks, that is, that a parser builds structures in comprehension, a generator builds structures in production, and a grammar is shared between these and also plays a central role in acceptability judgments. One can distinguish tasks and levels of analysis without committing to distinct mechanisms.

In other work, we have argued that it is beneficial and feasible to treat the structure-building system used in comprehension and the grammar as the same cognitive system (Phillips 1996, Phillips & Lewis 2013). Evidence that the distinction between the real-time structure-building system and the grammar is unnecessary comes from two broad domains. First, rapid structure-building processes during comprehension are highly grammatically sensitive (Lewis & Phillips 2015, Phillips et al. 2011). Second, standard grammatical analysis may benefit from assuming a structure-building system that proceeds in the same order as comprehension and production processes (Bianchi & Chesi 2014, Kempson et al. 2001, Phillips 2003, Shan & Barker 2006, Steedman 2000). However, there is little benefit in conflating the parser and the grammar if the parser and the generator cannot also be conflated. In fact, if the parser and the generator are distinct cognitive mechanisms that assemble the same representations, then it is necessary to have a third cognitive mechanism that defines the possible representations, namely a grammar. In other words, the choice is between one cognitive mechanism and three; two is not an option.

3. PREVIOUS PROPOSALS

We are certainly not the first to claim that parsing and generation share the same mechanisms. In this section, we review previous claims in psycholinguistics and neurolinguistics about the relationship between comprehension and production. We situate our current account in relation to two broad classes of claims: the interactionist view and the single-mechanism view.

3.1. Interactionist View

Many previous claims about the comprehension–production relationship can be classified under what we call the interactionist view. This view claims that comprehension mechanisms and production mechanisms are distinct, but they interact heavily during a single act of understanding or speaking.

Levelt (1983) raised the possibility that self-monitoring during speaking is carried out by comprehension mechanisms. This contrasts with the claim that self-monitoring is carried out by a separate mechanism internal to the production system (see Postma 2000 for review), which is an interactionist claim in the respect that some subtasks of production are performed by a generator-independent parser. The empirical status of this claim is beyond the scope of this review (see Hartsuiker & Kolk 2001 and Huettig & Hartsuiker 2010 for an overview).

The interactionist hypothesis regarding self-monitoring concerns the use of the parser during production tasks. Some psycholinguists have discussed possibilities in the other direction, that is, the use of generation mechanisms during comprehension tasks. For instance, Federmeier (2007) argued, based on evidence that the left hemisphere of the brain is critical in generating lexically specific prediction, that linguistically fine-tuned prediction is the product of production mechanisms, which arguably reside in the left hemisphere. Similarly, Pickering & Garrod (2007, 2013) proposed an interactive model of language processing in which parser-independent production implementers generate an internal representation of yet-to-be-heard elements of the sentence. Dell & Chang (2014) also claimed that their simple recurrent neural network model predicts upcoming words in sentence comprehension in much the same way as their system produces sentences.[1] Aside from the claim that prediction is a function of production mechanisms, Garrett (2000) discussed the possibility that the generator plays an important role in structural ambiguity resolution in sentence comprehension by taking lexical elements identified by the comprehension system and combining them with discourse knowledge to generate structures that are plausible in the current context. The structural representations created by the generator can be used to filter the candidate structures proposed by the parser. All of these claims are interactionist in the sense that they all assume a parser-independent generator.

Another kind of interactionist claim, which we call external interactionism, is the claim that comprehension and production interact with each other via the external world, namely, via the corpus that speakers generate and that comprehenders experience (Gennari & MacDonald 2009, MacDonald 2013). In this view, speakers have certain biases in producing certain sentences (e.g., animate entities tend to be mentioned first), which skews the distributional patterns in speech corpora. This pattern is learned by comprehenders in such a way that rarer patterns are more difficult to comprehend than more frequent patterns. We agree that something similar to the processes described by external interactionism may plausibly happen, but this account establishes the link between comprehension and production via the external world, rather than within an individual's mind.

3.2. Single-Mechanism View

Another class of claims posits that the cognitive mechanisms that are responsible for building the structural representation of sentences are identical in comprehension and production. We call this the single-mechanism view. The possibility of shared mechanisms has been repeatedly mentioned in the literature.

Kempen (2000) argued that comprehension and production processes have much in common. For example, both speakers and comprehenders are susceptible to agreement attraction (see Section 4.3.2). Based on such similarities, he suggested that the mechanisms for grammatical encoding (i.e., generation) and decoding (i.e., parsing) are shared. Kempen et al. (2012) also offered empirical evidence that speakers override comprehended sentence structures with produced sentence structures when paraphrasing. They compared the response latency of anaphoric pronouns in a paraphrasing task in which participants were asked to paraphrase direct speech (e.g., *The angry headmaster complained:* "*I have seen a nasty cartoon of myself in the hall*") into indirect speech (e.g., *The angry headmaster complained that he has seen a nasty cartoon of himself in the hall*). They found that participants did not slow down at the ungrammatical reflexive *himself* when the direct speech

[1] In this review, we highlight this parallel between Dell & Chang's (2014) model and other interactionist proposals. However, in other respects, their proposal is similar to a single-mechanism model.

sentences contained a mismatching reflexive (e.g., *The angry headmaster complained:* "*I have seen a nasty cartoon of himself in the hall*"), despite readily detecting the same anomaly in a self-paced reading task. They suggested that the syntactic representation of what participants understood used the same workspace as the syntactic representation of what they said. Kempen (2014) subsequently proposed a model that handles structure-building processes in comprehension and production with a single processor.

Finally, it is worth noting similar attempts in computer science to integrate the parser and the generator. This general framework is termed bidirectional grammar (e.g., Appelt 1987). Although this approach generally commits only to the position that the grammar can be integrated without claiming that the parser–generator can be, it has also been suggested that the architecture of the processing mechanism can also be integrated (Shieber 1988).

4. CURRENT PROPOSAL

The view advanced in this article is a version of the single-mechanism view. However, as it currently stands, the claim that parsing and generation mechanisms are identical remains somewhat vague. We must first clarify what it means for the parser and the generator to be identical. To this end, we classify identity claims into three levels.

4.1. Levels of Identity

There are at least three levels at which one can maintain the parser–generator identity claim. First is the claim that the parser and the generator share the same grammar. This is not especially controversial, as what a speaker can understand and what they can say normally obey the same grammatical constraints. We call this claim representation-level identity: The output representation of parsing and generation is the same. In the vast majority of cases, sentences that are judged to be unacceptable in comprehension are also avoided in production (but see Section 5.2 for discussion). Experimentally, structural priming occurs from comprehension to production (Bock et al. 2004) and from production to comprehension (Kim et al. 2014), suggesting that whatever is primed is shared between comprehension and production. Additionally, neuroimaging evidence suggests that overlapping neural resources are used during comprehension and production (Menenti et al. 2011, Segaert et al. 2011). Thus, at least the representations constructed during understanding and speaking are overwhelmingly the same.

Second, not only the representations but also the mechanisms by which those representations are built during speaking and understanding could be identical. We call this possibility mechanism-level identity.

Third, the procedures for building sentence structures could be identical in both speaking and understanding. We call this algorithm-level identity. Parsing and generation algorithms might specify which parts of a sentence representation are created first, second, and so on. Under the algorithm-level identity view, this order matches between parsing and generation. In principle, algorithm-level identity could hold without mechanism-level identity being true. However, we consider this unlikely, so we assume that algorithm-level identity entails mechanism-level identity.

These three levels of identity claims are, in the order discussed above, progressively harder to maintain as the relationship between the parser and the generator gets tighter. As we note above, the tighter the relationship between the parser and the generator, the more plausible is the transparency between grammar and real-time structure building. In the following sections, we evaluate the mechanism-level and algorithm-level identity claims, taking the representation-level identity as given.

4.2. Evaluating the Mechanism-Level Identity View

We evaluate the mechanism-level identity view by breaking it into several testable questions that we can address using existing research. The list is by no means exhaustive, but it is not random, either. Most properties that we focus on are research topics in their own right in psycholinguistics. Our aim is to show that the mechanism-level identity view is testable, plausible, and relevant to existing psycholinguistic research.

4.2.1. Long-term memory access. Lexical access, a relatively simple and well-studied process, is unequivocally involved in parsing and generation. It is often suggested that lexical access is based on content-addressable memory mechanisms [e.g., connectionist models of lexical access like those of McClelland & Elman (1986) in comprehension and Roelofs (1992) in production; but see Forster (1992) for the involvement of a serial mechanism]. The mechanism-level identity view claims that the mechanism is identical in parsing and generation.

How can a memory mechanism for comprehension and production be the same when the input to each is different in kind? A key property of content-addressable memory mechanisms is the fact that items in memory are accessed in parallel by matching the featural contents of memory items and retrieval cues. This property removes the need to assume distinct mechanisms for lexical access in comprehension and production. To demonstrate this, consider how a single content-addressable memory mechanism can interact with different modalities in other domains of cognition, using the case of recalling memories of real-world events as an example. This task involves accessing episodic memory, and it can be accomplished using various cues, including visual, auditory, and olfactory cues, or even more abstract cues like a person, place, or thing that is part of the target episodic memory. Despite the many different kinds of input, we do not conclude that there are distinct memory mechanisms for each type of cue. In this sense, a single memory mechanism can use different kinds of inputs.

Furthermore, it is not accurate to say that the inputs to lexical access are entirely different in speaking and understanding. There is evidence that multiple types of cues can be used in parsing and generation. For example, as noted by Pickering & Garrod (2007), lexical access in generation is helped by the existence of phonological cues associated with the target item. This has also been shown in picture–word interference studies, where seeing phonologically similar words helps speakers produce the target word faster, both in isolated production tasks (e.g., Lupker 1979, Schriefers et al. 1990) and in sentence-level production tasks (e.g., Meyer 1996). Meanwhile, lexical access in parsing, like that in generation, can benefit from semantic cues. This benefit can be seen in lexical priming effects (e.g., Neely 1977) and in lexical prediction effects using event-related potentials (DeLong et al. 2005, van Berkum et al. 2005) or visual-world eye tracking (e.g., Altmann & Kamide 1999).

There is also suggestive evidence that syntactic cues are used for lexical access in similar ways. In the case of comprehension, Wright & Garrett (1984) showed that lexical recognition is facilitated when the syntactic category of the target word is predictable from the prior syntactic context, independent of meaning. In production, it is well known that substitution and exchange errors rarely occur between words of different syntactic categories (Nooteboom 1969). In an experimental context, Momma et al. (2016), using a novel sentence–picture interference task, showed that the semantic interference effect in picture naming that is normally observed between semantic associates (e.g., *walking* and *running*) disappears when the two associates mismatch in syntactic category (e.g., *walking* as a noun and *running* as a verb). This result suggests that lexical competition is restricted to a specific syntactic category: Speakers are able to restrict their retrieval to nouns when accessing a noun.

In sum, we have evidence that phonological, semantic, and syntactic cues are used, when available, for lexical access both in comprehension and in production. This conclusion follows from the view that a single content-addressable memory mechanism is involved in lexical access in both parsing and generation.

The argument that we apply to lexical access may also hold for units larger than a single word. It is reasonable to assume that memory encodings of structural configurations larger than a word are stored and accessed in parsing and generation, as in many computational models of parsing (e.g., Lewis & Vasishth 2005, MacDonald et al. 1994, St. John & McClelland 1990, Vosse & Kempen 2000). Just like lexical memory, structural memory may be associated with semantic and phonological cues as well as syntactic cues. For instance, the double object dative construction (e.g., *John gave him an apple*) might be associated with semantic features such as transfer of possession and completion of transfer events (e.g., Green 1974). In this view, structural memories may have semantic content independent of the lexical items that fill them. Via content-addressable memory access, structural memories could be retrieved using semantic content as a cue, both in comprehension and in production. The same goes for phonological cues. For example, certain items in structural memory may be associated with prosodic cues due to systematic correspondence between syntactic and prosodic structures. An empirical advantage of this view is that the rapid use of message-level information and prosodic information in structural processing is expected in both parsing and generation. The rapid use of message-level information in parsing is well documented (e.g., Tanenhaus et al. 1995), and the rapid use of semantic cues in generating syntactic structure is something that speakers do all the time. In addition, predictive processes in comprehension are likely based on event memory representations, which presumably share a representational format with message representations (e.g., Chow et al. 2016, Kim et al. 2016). Likewise, the rapid use of prosodic cues to select an appropriate syntactic structure is also documented in parsing (e.g., Snedeker & Trueswell 2003), although it is unclear how prosodic cues can be used for structure generation in speaking. Syntactic cues are clearly used during both parsing and generation. For example, projection of phrase structure can be understood as the process of accessing phrasal nodes in memory using syntactic category as a retrieval cue. The verb's structural information (subcategorization) has also been shown to rapidly affect parsing (e.g., Trueswell & Kim 1998) and generation (e.g., Melinger & Dobel 2005, Pickering & Branigan 1998), and such findings plausibly reflect retrieval of relevant structural memories using the verb's subcategorization features as retrieval cues. In sum, memory for words and for structures may be accessed via phonological, syntactic, and semantic cues when they are available. Thus, a single content-addressable memory mechanism may underlie lexical and structural memory access in parsing and generation.

4.2.2. Eagerness of structural integration. Once a structural building block is retrieved from memory, it needs to be integrated into the developing representation of a sentence. In parsing, models that immediately integrate newly accessed items are described as strongly incremental (e.g., Crocker 1996, Lombardo & Sturt 2002, Schneider 1999, Sturt & Lombardo 2005). Those incremental models maintain a connected structural representation throughout the comprehension process, in contrast to some earlier parsing models, like that of Marcus (1980), that employed a look-ahead buffer. If the mechanism-level identity view is correct, we should expect parsing and generation to be equally eager in terms of how structural integration occurs.

In evaluating this view, it is important to note that the term incrementality is commonly used in production research, but often in a different sense than in the parsing literature. In production, the term incrementality is often used to refer to the degree of synchronization between planning and articulation processes (e.g., Ferreira & Swets 2002; Iwasaki 2010, pp. 131–51; Konopka 2012; Norcliffe et al. 2015; Wagner et al. 2010) and is closely associated with cascading of information across different levels of processing (De Smedt 1996, Kempen & Hoenkamp 1987, Levelt 1989). This is not the same as the notion of incrementality used in parsing. Incrementality in parsing refers to the speed and grain size of integration and updating within a level of representation.

In production, it is intuitively the case that speakers do not always utter words immediately upon planning them. Speakers can certainly plan an entire sentence before starting to say it if they so choose. Experimentally, the scope of advance (lexical) planning in speaking has been shown to vary across studies (e.g., Allum & Wheeldon 2007, 2009; Griffin 2001; Meyer 1996; Smith & Wheeldon 1999; Wheeldon & Smith 2003) and even within an individual study, suggesting that how long we wait to utter a planned word is under strategic control or modulated by resource availability (Ferreira & Swets 2002, Konopka 2012, Wagner et al. 2010). However, this does not mean that the generator is less incremental than the parser. The relevant question is whether the generator rapidly integrates retrieved words or structures to maintain a connected structure, in the same way that the incremental parser rapidly integrates incoming words into the structural parse. There is little existing evidence on this issue, but we take it as a reasonable initial assumption that parsing and generation closely parallel one another in this regard.

4.2.3. Grain size of structure-building unit. After building some structure, comprehenders and speakers use it to understand and speak, respectively. In both comprehension and production, structures must expand by a certain increment, and the size of this increment determines how much structure speakers and comprehenders build before they use it for speaking or understanding, respectively. In the mechanism-level identity view, the grain size of the units by which structures expand should match between parsing and generation.[2] The grain size can be studied by examining how frequently structure-building and poststructural processes (interpretation and articulation) can interleave in comprehension and production.

Modern parsing models normally assume that little needs to be known before interpretation can start. Interpretation of a partial input can and often does occur immediately as each word is received (e.g., Kamide et al. 2003, Kutas & Hillyard 1980, Marslen-Wilson 1973). Intuitively, the parser does not need to know an entire clausal structure before it can start to interpret the sentence. Thus, the grain size of structure-building units in parsing is usually considered to be rather small and definitely smaller than a clause.

In contrast to most modern comprehension models, some influential production models assume that speakers must plan a lot of structure before they can start articulation (e.g., Bock & Cutting 1992, Boomer 1965, Ferreira 2000, Fodor et al. 1974, Ford & Holmes 1978, Griffin & Weinstein-Tull 2003). For instance, Garrett (1980, 1988) assumes that the abstract representations of words (lemmas), along with their grammatical roles (subject, object, verb, etc.), are all specified before phonological encoding initiates. More recently, Ferreira (2000) proposed a production model based on lexicalized tree-adjoining grammar (e.g., Joshi & Schabes 1997), in which basic clausal structure, along with a verb head, is specified before the initiation of phonological encoding. This model follows a long tradition in production research in which the performance unit is assumed to be a clause rather than a word (see Bock & Cutting 1992 for a historical overview).

Based on previous research, we can be confident that comprehenders do not need to know (or at least do not need to be certain about) the upcoming sentence structure to initiate interpretive processes (Aoshima et al. 2009, Kamide et al. 2003, Kutas & Hillyard 1980, Marslen-Wilson

[2] In production research, the grain-size question is often asked in the context of whether sentence production is incremental (e.g., Levelt 1989, De Smedt 1996, Wagner et al. 2010). However, we reserve the term incrementality to mean the immediate integration of retrieved words into grammatical structures, to draw a closer parallel between parsing and generation.

1973). In production, however, we still know relatively little about how much structure speakers need to plan before articulation is initiated.[3] Certainly, there are models that assume a small grain size for structure-building units (e.g., De Smedt 1996, Levelt 1989). However, much previous work on sentence planning has focused on whether a particular word that occurs downstream in a sentence is accessed before the first word of the sentence is articulated, and relatively little attention has been paid to the question of whether structural aspects of the sentence need to be planned ahead (but see Wheeldon et al. 2013 for relevant work). This issue is important in answering the grain-size question. If a large chunk of structure is planned without the words that fill it, then whether a particular downstream word is planned in advance is not informative about the size of the structural unit. Consequently, existing evidence about lexical look-ahead does not necessarily tell us whether the structural representation needs to be planned ahead. Indeed, there is evidence that suggests that structural aspects of a sentence are planned prior to lexical access (Dell et al. 2008, Ferreira & Humphreys 2001, Momma et al. 2016, Nooteboom 1969).

Momma et al. (2017) recently tested whether speakers indeed plan basic clausal structure before sentence onset, as predicted by models of production that assume a large grain size (Bock & Cutting 1992, Boomer 1965, Ferreira 2000, Fodor et al. 1974, Ford & Holmes 1978), by combining structural priming with measurements of changes in speech rate throughout a sentence. Normally, structural priming is measured as an increase in the proportion of choices of one structure over another given a structural choice (Bock 1986; see Pickering & Ferreira 2008 for a review). For instance, if a speaker hears or says a prepositional dative (PD) sentence like *John gave an apple to Mary* before describing a picture involving a ditransitive event, they are more likely to use a PD construction in their subsequent description (e.g., *Bill sent a letter to his parents*). In contrast, we measured the effect of structural priming on speech rate during the production of ditransitive sentences (see Wheeldon & Smith 2003, Segaert et al. 2016 for studies that show effects of structural priming on speech onset latency). We expected that repeating the PD structure would speed up production, but the question was not whether but, rather, when in the sentence this speed-up effect would occur. If speakers plan the structure of the verb phrase prior to utterance onset, then they should be faster to begin saying a sentence with the same verb phrase structure. If speakers instead construct the verb phrase structure while they are uttering the preceding part of the sentence, then they should speed up in the middle of the sentence, at the point when they have to make a decision about the structure of the verb phrase. The results showed that speakers are not faster to begin uttering the sentence, but they are faster to say the verb itself when the ditransitive structures are primed. Assuming that the timing of priming effects corresponds to the timing of planning, these results suggest that speakers can and do start saying the verb itself without planning the internal structure of verb phrase, which, in turn, suggests a rather small grain size of structure building in generation, consistent with a standard property of modern parsing models.

4.2.4. Structural decision making. One of the primary tasks of the parser is to resolve structural ambiguity in the input. This is not the case for the generator. Speakers generally know what

[3]Gleitman et al. (2007) showed that, in an event–picture description task, perceptual attention modulates the choice of sentence structure; for instance, speakers are more likely to say a passive sentence when the patient entity in a transitive picture is perceptually cued. Some researchers suggest that this result offers strong evidence for word-by-word production with little or no structural look-ahead (e.g., Bock & V. Ferreira 2014, Konopka 2012). We disagree with this interpretation. The evidence suggests an early influence of conceptual processes on linguistic formulation (as Gleitman et al. 2007 already argued), but it does not argue against advance planning of structure beyond the initial part of the sentence. These are logically independent issues.

they want to say. How is it possible that the parser and the generator are the same given this difference? Again, a task difference need not imply a mechanism difference. Although generation does not face a message ambiguity problem, both the parser and the generator have to make structural decisions. The parser needs to choose a structure from among structural alternatives that are consistent with the sound input, whereas the generator needs to choose a structure from among structural alternatives that are consistent with the same message (e.g., choose among active versus passive structures or double object versus prepositional object structures). In other words, the parser and the generator share the same computational goal of selecting a structural representation that is consistent with the input. The question is whether the same mechanism underlies this computation.

In parsing research, there has been a major line of research on whether the candidate structural analyses are generated serially or in parallel (Lewis 2000; see Clifton & Staub 2008 for discussion). The same question can be asked, and has been asked under different terms, in production research. One theoretical choice point in production models is whether structural alternatives are selected competitively (e.g., Dell & O'Seaghdha 1992). Competitive models assume parallelism in selecting structural alternatives, whereas noncompetitive models usually assume serial processes (Ferreira 1996). Parallel parsing models and competitive generation models predict that processing is more costly when there are multiple structural alternatives, even before the input becomes incompatible with one of the preferred structural alternatives. Contrary to this prediction, one notable empirical parallel between parsing and generation research is that the (temporary) availability of structural choice (e.g., ambiguity in parsing and structural flexibility in generation) facilitates rather than inhibits processing until the structure becomes incompatible with the input (Ferreira 1996, Traxler et al. 1998). This is suggestive evidence that the same noncompetitive mechanism for structural decision making might be at play in both parsing and generation.

4.3. Long-Distance Dependency Formation

Both parsing and generation involve establishing long-distance dependencies, including filler–gap dependencies (e.g., *wh*-questions, relative clauses), anaphoric dependencies (e.g., reflexives, pronouns), and morphosyntactic dependencies (e.g., subject–verb agreement). In the mechanism-level identity view, the parser and the generator should engage the same mechanisms for processing each of these dependencies, although they may exhibit different surface phenomena due to differences in the content and timing of the input.

4.3.1. Filler–gap dependencies. In parsing, two prominent processes presumed to be involved in filler–gap dependencies are active gap search (e.g., Fodor 1978) and the reactivation and integration of fillers (e.g., Bever & McElree 1988, McElree & Bever 1989). In active gap search, the parser initiates a search for a potential gap site upon encountering a filler (e.g., *wh*-words, evidence for a relative clause). As a result, the parser slows down when a potential host for the gap is filled by overt elements (filled-gap effect; Crain & Fodor 1985, Stowe 1986) or even when the first-encountered verb (in a nonisland context) is an intransitive verb that cannot host a gap (hyperactive gap filling; Omaki et al. 2015). This suggests that the parser actively creates a gap representation as soon as it encounters a filler.

Is the process of building filler–gap dependencies similarly active in production? We suspect that it is, but this does not mean that we should expect to find filled-gap effects in production in the same constructions that elicit them in comprehension. In this case, as in other cases, parsing and generation differ in terms of their starting point. Comparing surface effects can be misleading. In comprehension in English, the filler signals that a filler–gap dependency is present. The parser immediately knows that there is a gap in the sentence but does not know where it is. Filled-gap effects arise when the parser commits to gap sites that turn out to be in the wrong position. In production, in contrast, we can presume that speakers have a better sense of the meaning of the sentence and, thus, a better idea of where the gap should be. For example, in an English direct *wh*-question, the speaker must commit early to the existence of a filler because the filler is uttered first; at that point, the speaker should already know what is being questioned, that is, what is in the gap position. However, at the point of committing to a filler–gap dependency, the speaker may know the message but might not yet know how that translates into linguistic form and, thus, whether the filler–gap relationship will turn out to be grammatically licit. Therefore, the production equivalents of filled-gap effects are cases where the producer creates a filler–gap dependency and then discovers that it is illicit, because the intervening material creates a syntactic island, requiring the gap to be replaced with a resumptive pronoun. For example, Ferreira & Swets (2005) used a picture description task to elicit sentences with relative clauses. In the critical conditions, the filler–gap dependency turned out to include a *wh*-island and thus required a resumptive pronoun instead of a gap (e.g., *This is the donkey that I don't know where it came from*). Ferreira & Swets (2005) used measures of speech rate to show that speakers detected this problem in advance of articulating the *wh*-island. This suggests that the generator actively posits gaps before planning the syntactic structure of the clause containing the gap.

Another process in filler–gap dependency is the integration of fillers at the gap site. This process has been demonstrated in experiments that probe whether the filler representation is reactivated at the gap site (McElree & Bever 1989) using such paradigms as cross-modal lexical priming (Nicol & Swinney 1989), probe recognition tasks (Bever & Sanz 1997, MacDonald 1989), and online semantic anomaly detection tasks (Wagers & Phillips 2014). This process is also suggested by electroencephalogram effects found at the completion of entirely well-formed filler–gap dependencies (Kaan et al. 2000, Phillips et al. 2005). We know of no model of production that explicitly specifies what happens at the gap site. In both comprehension and production, the gap site marks the completion of the dependency, but because producers know what they mean to say, this completion involves less reduction in uncertainty than the corresponding step in comprehension. In the mechanism-level identity view, however, the retrieval of fillers might be expected to occur when the generator needs to link the filler with the gap position. Some preliminary evidence suggests that this is the case (Momma et al. forthcoming). Thus, the parsing model provides a reasonable default hypothesis about what happens at the gap site in production.

4.3.2. Subject–verb agreement. In many languages, including English, the parser and the generator must be able to establish morphosyntactic agreement between the subject and the verb in terms of grammatical features, such as number features. In this process, both the parser and the generator are known to be susceptible to interference from nearby material (Bock & Miller 1991, Wagers et al. 2009). For example, speakers often misproduce a plural verb when the subject noun is singular but a structurally irrelevant plural noun is present: *the key to the cabinets are* . . . . Likewise, comprehenders often fail to notice the ungrammaticality of the plural verb when the same sentence is presented to them. As in filler–gap dependency processing, logically speaking, the parser and the generator could share or not share the same mechanism for computing subject–verb agreement. Whatever the correct explanation of this phenomenon is (see, e.g., Eberhard et al. 2005, Wagers et al. 2009 for two different accounts), occasions when agreement processing is successful and when it is unsuccessful seem generally to overlap (see also Bock & Cutting 1992). This is surprising if the parser and the generator compute subject–verb agreement using different mechanisms.

However, despite the similarities in the surface effects of agreement attraction, Badecker & Lewis (2007) caution that different sets of cues are available for establishing subject–verb agreement in comprehension and production. In comprehension, the verb form is provided to the comprehender, so its morphological features (e.g., number, gender) can be used as cues for retrieving the subject. In production, the speaker's task is to choose an appropriate verb form, so the verb cannot possibly provide morphological retrieval cues for accessing the subject. This contrast does not mean that the mechanism for establishing subject–verb agreement, namely content-addressable memory, is different in speaking and understanding, but it does raise the possibility of finer-grained differences between agreement attraction in production and in comprehension. It also poses a challenge for algorithm-level identity with respect to subject–verb agreement.

4.3.3. Anaphoric dependencies. Both the parser and the generator must be able to establish referential dependencies between anaphoric elements (e.g., *herself*, *himself*, *them*) and their antecedents while matching grammatical features such as number and gender. This process is superficially similar to subject–verb agreement: Both involve establishing a morphosyntactic dependency with respect to some grammatical features. However, unlike in subject–verb agreement, the parser and the generator seem to behave differently. Bock et al. (1999) reported that reflexive number agreement is susceptible to interference from nonsubject interveners in generation. In contrast, this attraction effect is either weak or nonexistent in parsing (Dillon et al. 2013). We now know of situations that more reliably elicit attraction effects for reflexives (Parker & Phillips 2017), but these require more specific configurations. If this discrepancy is real, it suggests that the task, the mechanism, or the procedures for establishing anaphoric dependencies are different between generation and parsing. We currently do not know which of these factors is to be blamed or if the observed empirical pattern is consistent across studies.

This discrepancy may be caused by the differences in starting point. In parsing, comprehenders use agreement morphology to encode coreference relationships. In production, speakers use coreference information to encode agreement morphology. Thus, the parser needs to rely heavily on morphological information, whereas the generator needs to rely heavily on semantic (coreference) information. Such a difference in the representational type of retrieval cues does not exist in subject–verb agreement. It is possible that retrieval processes using morphological cues versus semantic cues with respect to antecedent–reflexive dependencies are differentially sensitive to grammatical constraints (i.e., that a reflexive must be locally c-commanded by its antecedent). The challenge of this approach is to explain exactly why retrieval based on morphological cues on reflexives should be more sensitive to grammatical constraints than retrieval based on semantic cues. This issue is in need of further investigation.

4.3.4. Is mechanism-level identity plausible? In this section, we have derived some predictions and questions from the mechanism-level identity view and reviewed relevant empirical findings, ranging from lexical access to long-distance dependency formation. We have argued that mechanism-level identity is largely consistent with what we know about parsing and generation. Our knowledge of production processes is clearly more limited, but addressing these processes in parallel with comprehension is both feasible and instructive.

4.4. Evaluating the Algorithm-Level Identity View

In the previous section, we ask whether the same structure creation mechanisms are engaged in parsing and generation, but we do not commit ourselves to the idea that structures are assembled in the same order in both tasks. If input is provided to the parser and the generator in different orders, then the same mechanisms could build structures in different orders. The order of structure building in parsing is relatively fixed because the comprehender is at the mercy of the order of the input. In generation, the speaker has more latitude, at least in principle. The sentence has to be uttered using the correct word order, but that is no guarantee that the structure is planned in the order that the words are uttered. In this section, we examine the stronger claim that the order of structure-building operations is the same in parsing and generation. We call this the algorithm-level identity view.

4.4.1. Manner of structure building. The parsing literature distinguishes between constituents built in a bottom-up and those built in a top-down fashion. In bottom-up structure building, words are accessed first, and then structures are built by combining retrieved words. In top-down structure building, phrasal structures are built first, and then retrieved words are inserted into available structural positions. These approaches differ in the relative timing of structural versus lexical processes, and we can test their status in parsing and generation.

In parsing research, it is widely acknowledged that a mix of bottom-up and top-down parsing methods are necessary to parse a sentence. Miller & Chomsky (1963) noted that consistently left-branching structures (e.g., *John's brother's cat despises rats*) and consistently right-branching structures (e.g., *the dog that chased the cat that bit the rat likes the cheese*) do not cause substantial processing difficulty relative to structures with mixed branching direction (e.g., center-embedded sentences). This result would be unexpected if the human parser relied on purely bottom-up or purely top-down structure building. Assuming standard phrase structure rules, a purely bottom-up parser cannot process a left-branching structure without substantial memory cost. Meanwhile, a purely top-down parser cannot process right-branching structures without making many incorrect structural predictions. A solution is to adopt a mixed method, in which bottom-up input filters top-down structure building, as in a left-corner parser. The left-corner model predicts that center-embedded sentences are hard and left-branching and right-branching sentences are easy to process. Thus, this model captures the circumstances in which the human parser experiences difficulty, and it has been adopted by models of comprehension (e.g., Abney & Johnson 1991, Johnson-Laird 1983, Lewis & Vasishth 2005, Resnik 1992). We thus take this model as a good first approximation of how the human parser processes a sentence.

Turning to generation, some models of production assume a radically top-down approach, in which the basic structure of a sentence is planned before lexical items are integrated into the structure (e.g., Garrett 1980, 1988). Other models of production adopt a more bottom-up approach, in which structures are built as a result of retrieval of lexical items, particularly the head of the phrase (e.g., Bock & Levelt 1994, Levelt 1989). Thus, there is a potential mismatch in how existing parsing and generation models build structures.[4]

We argue that both top-down and bottom-up structure building are used in generating individual sentence structures. One type of evidence for top-down structure building comes from the experiment described in Section 4.2.3. Momma et al. (2017) found that the speed-up effect of repeating a verb phrase structure in a ditransitive sentence preceded the speed-up effect of repeating a noun internal to that verb phrase. Assuming that speed-up due to repetition priming indicates the time when the repeated material is planned, this suggests that structural representations are constructed before lexical planning, at least when producing a ditransitive verb phrase. This

[4]The model described by Levelt (1989, chapter 7) is not purely bottom-up. For example, the model allows a verb's category node to be created on the basis of the need to have a predicate, rather than on having identified a specific verb. This is a limited case of top-down structure building.

result can be understood as evidence for top-down structure building in the verb phrase. As for bottom-up structure building, there is ample evidence that the availability of a word determines which sentence structure is used (Bock 1987 and much subsequent work). One interpretation of this availability effect is that lexical access precedes structure building; that is, this effect provides evidence for bottom-up structure building. When combined, these pieces of evidence suggest that generation involves both bottom-up and top-down structure-building processes.

Certainly, this evidence falls short of showing that the generator builds structures in exactly the same order as a left-corner parser. We consider this possibility rather unlikely. For example, when building a noun phrase in a language with grammatical gender, it is unlikely that the determiner is planned before the noun head. However, the mixture of top-down and bottom-up structure building may be shared between parsing and generation. The difference in the order of derivation might simply reflect differences between the two tasks, which affect which pieces of information become available to the language processor and when. In a normal comprehension task, the parser receives input in a fixed linear order, so the parsing algorithm ends up looking like a left-corner parser algorithm. In contrast, in picture description tasks, for example, information that corresponds to the head noun is what hits speakers' eyes. Thus, the generation algorithm may use the head noun to filter top-down structure building, ending up looking like a head-driven algorithm in noun phrase production. This could be sufficient to lead to differences in which parts of the sentence are built in a top-down versus a bottom-up fashion.

4.4.2. Order of structure building. Even if both parsing and generation involve a mix of top-down and bottom-up structure building, there is freedom in the order of structure building that could give rise to differences between parsing and generation algorithms. Indeed, in the previous section, we acknowledge the implausibility of an exact match in the order of structure building between parsing and generation. In this section, we explore the possibility that this flexibility in the order of structure building could be shared between parsing and generation.

It is unlikely that the planning of lexical items in production proceeds in an exactly left-to-right fashion. For example, the determiner in a noun phrase is likely planned after the head noun, especially in gendered languages like German. There is also evidence that a sentence-medial adjunct is planned after the sentence-final verb in some English intransitive sentences (Momma et al. 2017). However, it is also increasingly unclear whether parsing proceeds in an exactly left-to-right order due to the involvement of predictive processes (Altmann & Kamide 1999, DeLong et al. 2005, Kamide et al. 2003, Lau et al. 2006, Staub & Clifton 2006, van Berkum et al. 2005). For example, when the parser predicts a noun phrase that occurs later in a sentence, it is possible that the head is planned before the determiner or adjective that modifies it. Thus, when the parser builds structures ahead of the phonological input, it might behave like the generator in terms of the order of structure building. Conversely, when the generator is constrained by phonological input, as in a sentence completion task where the preamble of the sentence is provided to the speaker, the generator might behave like the parser in terms of the order of structure building. For example, speakers can be given the determiner phonologically as a preamble, and they should have no difficulty completing the rest of the noun phrase. In this case, again, differences between parsing and generation might simply reflect differences in what is available in the different task environments.

4.4.3. Is algorithm-level identity plausible? In this section, we have derived some empirical questions from the algorithm-level identity view and discussed some findings that relate to the order in which the parser and the generator build sentence structures. We have argued that the algorithm-level identity view is largely consistent with what we have learned so far, but that it is likely necessary to assume some flexibility in how structures are built in parsing and generation.

5. CHALLENGES

Despite the theoretical appeal of a unified account, there are reasons to think that parsing and generation may be supported by distinct mechanisms. These include (*a*) neuropsychological and developmental double dissociations, (*b*) differences between acceptability and producibility, and (*c*) differences in maximal processing speed. We briefly review each challenge and its seriousness.

5.1. Arguments from Double Dissociation

Classic neuropsychological investigations have suggested that patients with left frontal versus temporal lobe damage can show selective impairments in expression or perception of language, respectively. Historically, Broca's and Wernicke's aphasia were thought to be deficits of production and perception of speech, respectively, and this double dissociation led to comprehension and production being localized to distinct regions in the brain in the Wernicke–Geschwind model (Geschwind 1967; also see Ben Shalom & Poeppel 2008). Following the logic of double dissociation, these selective impacts imply that the parser and the generator are distinct mechanisms.

Also, it has been noted repeatedly in the developmental literature that language production is normally delayed compared to comprehension (e.g., Keenan & MacWhinney 1987). The reverse is also true in some domains of language. For example, 4–6-year-old children often misinterpret sentences like *Ernie washed him* to mean *Ernie washed himself* (Chien & Wexler 1990; but see Conroy et al. 2009), but corresponding errors are not found in production (Bloom et al. 1994). Thus, we find cases of double dissociation in the developmental time course. This suggests that some components of parsing and generation might be distinct in children.

The interpretation of double dissociations, however, is not so straightforward. Dissociations of comprehension and production tasks do not entail that the mechanisms are dissociable. In neuropsychology, Caramazza & Zurif (1976) have shown that Broca's aphasics' comprehension is far from normal, especially for sentences with noncanonical structures like passives and object relative clauses. Thus, Broca's aphasia may reflect, for example, a deficit in mapping morphosyntactic information and semantics, which are necessary for both systematic comprehension and fluent production. Wernicke's patients' speech production is also far from normal. In addition, at least some Wernicke's patients have preserved reading comprehension (Ellis et al. 1983). Because of this, it has been claimed that Wernicke's aphasics may have trouble mapping phonological and semantic sources of information onto each other. If these explanations are correct, it could be argued that the apparent double dissociations simply reflect the differential demands of individual subtasks in comprehension and production. The same argument could be made for developmental double dissociations. The challenge for an advocate of the single-mechanism view is to show explicitly how the same underlying deficit yields different surface effects. An advocate of a two-mechanism approach does not face this challenge, but must instead address the related challenge of why superficially different aspects of speaking and understanding are frequently impacted together.

5.2. Differences in Acceptability and Producibility

Speakers often produce sentences that they themselves find unacceptable. A well-known case in English is resumptive pronouns inside syntactic islands (e.g., McDaniel & Cowart 1999, Zukowski

& Larsen 2004). In an elicited production study by Ferreira & Swets (2005), speakers produced sentences like **This is the donkey that I don't know where it lives.* The same sentences were, however, judged to be unacceptable. This mismatch between acceptability and producibility poses an apparent challenge to the notion of shared mechanisms for comprehension and production. However, it is again unclear whether this difference is due to a task difference or a difference in mechanisms. In production tasks, speakers need to complete sentences, and this pressure can overcome the dispreference for certain structures. Such pressure does not exist in acceptability judgment tasks, where comprehenders simply need to provide a rating for a sentence.

5.3. Difference in Maximal Speed

After some amount of practice, at least, comprehenders are surprisingly good at understanding compressed speech (Foulke & Sticht 1969; see also MacKay 1987 for a discussion), which has a much faster speed than fluent speakers can possibly speak. This rate difference could suggest distinct mechanisms. But, again, it could also reflect task differences rather than different mechanisms. Speaking involves much open-ended decision making, whereas comprehenders face fewer and more constrained choices. Also, speakers have to move their articulators, whereas comprehenders merely have to build mental representations.

6. CONCLUSION

In this article, we have advanced the view that a single mechanism for building sentence structure may be sufficient for structure building in comprehension and production, synthesizing previous proposals and challenges on this issue. There are many superficial differences, but these may reflect input differences rather than distinct mechanisms. As argued above, this view is a prerequisite for maintaining a transparent relationship between grammar and real-time structure building, and it thus has far-reaching implications for the architecture of the human language system. This view also provides a useful framework for integrating largely independent research programs on comprehension and production by both constraining the models and uncovering new questions that can drive further research.

SUMMARY POINTS

1. Aligning the parser and the generator is a prerequisite for aligning theories of grammar and language processing.
2. We synthesize existing proposals and challenges regarding the relationship between parsing and generation.
3. We clarify what it means for the parser and the generator to be the same, and we identify a series of properties of structure-building mechanisms that could match or mismatch in parsing and generation.
4. We argue that fundamental properties of parsing and generation mechanisms are the same and that differing behaviors reduce to differences in the available information in either task.

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Errata

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